frontiers | Research Topics

Cognitive and motor skills in sports

Edited by
Sabine Schaefer, Karen Zentgraf and Kylie Ann Steel

Published in
Frontiers in Psychology
Frontiers in Sports and Active Living

ISSN 1664-8714
ISBN 978-2-8325-6655-8
DOI 10.3389/978-2-8325-6655-8

Generative AI statement
Any alternative text (Alt text) provided alongside figures in the articles in this ebook has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

About Frontiers

Frontiers is more than just an open access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

Frontiers journal series

The Frontiers journal series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the *Frontiers journal series* operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

Dedication to quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews. Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view. By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the *Frontiers journals series*: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area.

Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers editorial office: frontiersin.org/about/contact

Cognitive and motor skills in sports

Topic editors
Sabine Schaefer — Saarland University, Germany
Karen Zentgraf — Goethe University Frankfurt, Germany
Kylie Ann Steel — Western Sydney University, Australia

Citation
Schaefer, S., Zentgraf, K., Steel, K. A., eds. (2025). *Cognitive and motor skills in sports*. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-8325-6655-8

Table of contents

frontiers | Frontiers in Psychology

TYPE Editorial
PUBLISHED 14 July 2025
DOI 10.3389/fpsyg.2025.1629218

Check for updates

OPEN ACCESS

EDITED AND REVIEWED BY
Guy Cheron,
Université Libre de Bruxelles, Belgium

*CORRESPONDENCE
Kylie Ann Steel
k.steel@westernsydney.edu.au

RECEIVED 15 May 2025
ACCEPTED 26 May 2025
PUBLISHED 14 July 2025

CITATION
Schaefer S, Zentgraf K and Steel KA (2025) Editorial: Cognitive and motor skills in sports. *Front. Psychol.* 16:1629218.
doi: 10.3389/fpsyg.2025.1629218

Editorial: Cognitive and motor skills in sports

Sabine Schaefer[1], Karen Zentgraf[2] and Kylie Ann Steel[3,4,5]*

[1]Institute for Sport Science, Saarland University, Saarbrücken, Germany, [2]Work Unit Movement Science and Training in Sports, Institute for Sports Sciences, Goethe University Frankfurt, Frankfurt, Germany, [3]School of Health Science, Western Sydney University, Sydney, NSW, Australia, [4]MARCS Institute, Western Sydney University, Sydney, NSW, Australia, [5]Translational Health Research Institute, Western Sydney University, Sydney, NSW, Australia

KEYWORDS

attention, cognition, decision-making, movement, skill acquisition

Editorial on the Research Topic
Cognitive and motor skills in sports

Our Research Topic assembles 19 contributions that explore cognition and motor skills in sports. Conceptual issues are addressed in two of these papers including Loland et al. who propose an integrative approach in the formation of sports-specific movement-skill theories. The researchers suggest to first attribute phenomenological descriptions of the primary experiential qualities inherent in the execution of the respective skill. This should be followed by multilevel mechanistic analyses (based on biomechanics, motor control approaches, expertise studies, and cognitive science), and culminating in the systematization of findings and the formulation of sport-specific motor skills theories.

Huesmann and Loffing, with attention toward anticipation research, propose a framework to guide study design and reporting. Their paper details a first proposal for a 7-level classification of perception-action coupling conditions, with the defining dimensions of stimulus presentation and response mode orientation. The authors also provide the findings from a review of anticipation and racquet sport studies utilizing the classification system as a template for experimental protocol analysis, revealing underrepresentation of representative perception-action coupling conditions.

Seven contributions to this Research Topic address cognitive-motor dual-task situations across a diverse range of sports. Firstly, Wu et al. provide a review on the effects of cognitive-motor dual-task training, based on 10 acute and 7 chronic studies. For acute effects, studies consistently show performance deteriorations in dual- as compared to single-task situations. Conversely, studies exploring chronic effects show that systematic training in cognitive-motor dual tasking improves performances in cognitive-motor dual-tasks. Montalt-Garcia et al. provide depth to the Canadian Agility and Movement Skill Assessment (CAMSA) with cognitive challenges, resulting in six performance profiles in a large sample of secondary school students. The paper by Monz et al. combines ergometer rowing and Taekwondo exercises with an episodic memory task, revealing pronounced performance decrements in both cognition and motor functioning in the dual-task condition, across different age and expertise levels. Knöbel and Lautenbach tested soccer players with a 3-back working-memory task, either performed on a computer, or with a soccer-specific motor response (shooting toward a specific target location in space). The study reports a significant correlation between performances (response time and accuracy) in the two settings, indicating that the task may be a suitable diagnostic tool for soccer performance.

Klotzbier and Schott a continued the contributions that address cognitive-motor dual-task situations by asking soccer players to perform the classic Trail-Making test while also exposing them to modified versions of the test including movement through space (Trail-Walking test) or dribbling a soccer ball (Trail-Dribbling test). For the Trail-Dribbling test, the authors report shorter test durations for high-level compared to low-level players, with increased cognitive load accentuating differences. The authors conclude that the Trail-Dribbling test allows for an effective discrimination between high and low-level players in the age range of 14 to 17 years. Utilizing 322 elite athletes (ice hockey, closed skill sports, other team sports), Brinkbäumer et al. had subjects perform a tapping task, a visuo-verbal speed-reading task, and both tasks simultaneously. Dual-task costs were found for all sport groups, and costs were more pronounced in closed-skill athletes. For athletes from team sports and ice hockey, the authors did not find a relationship of dual-task costs to performance level. Amara et al. continued this dual task theme and assessed a mental rotation task with and without balance exercises in badminton and volleyball players. Unlike the other studies in the current Research Topic, which consistently found performance deteriorations under dual-task conditions, the reaction times of participants in the Amara et al. study were reduced when balancing concurrently.

An additional sub-theme to emerge amongst the papers submit to this Research Topic was the role of sensory input for sport skills with five submissions. Müller et al. manipulated visual input with stroboscopic glasses in a within-subjects design in Australian Rules football athletes, interrupting the perception-action cycle while kicking the ball at a goal. Interestingly, their study found no performance decrements in kicking accuracy. Continuing with visual factors, Nakazato et al. used an eye tracking device in a virtual table tennis environment with different types of ball trajectories, courses, and speeds. Their findings demonstrate that experienced table tennis players demonstrated lower mean and inter-trial variability in saccade endpoint error compared to novices, which may be indicative of more efficient identification of relevant stimuli. Nicklas et al. introduced a particularly novel study and assessed the role of visual fixations for interpersonal communication in elite sports. Eighteen expert beach volleyball players were exposed to game-like scenarios with high and low performance pressure. They found that higher pressure leads to more and longer fixations on teammates' faces, reflecting a higher need for communication without misunderstandings. In contrast to previous study's Rodrigues et al. explored the gaze behaviors of coaches rather than athletes. The authors showed differences in gaze durations in expert and novice coaches in a variety of game situations for videotaped futsal set pieces. Finally, Kassem et al. tested the eye movements relative to decision accuracy of elite junior Australian Rules football players with 14 brief video clips in two testing sessions in an 18-month time-interval. Participants with accurate decisions responded faster, and skilled participants demonstrated fewer fixations with shorter durations. The authors argue that the task may be a viable tool for Talent Identification and Development.

Our Research Topic also includes studies on embodiment, motor imagery, mental rotation, and skill learning. Luis del-Campo et al. assessed embodied planning in climbing and showed that the handholds where gaze was directed to during pre-planning were used more often than others. Further, experienced climbers ascend faster and look at non-used handholds for a shorter time compared to lesser-skilled climbers. For motor imagery, Tien and Chang re-examine the commonality and distinguishable aspects of motor imagery and execution via a response repetition paradigm. Their results show that motor representations of imagery and execution, when measured without subjective judgments, appear to be more distinguishable than traditionally thought. While Çiftçi and Yilmaz investigated action observation and motor imagery in an intervention study. For drop jump performance, an 8-week-intervention program with motor imagery sessions during video observation did not lead to improvements in physical performance, but there was a positive influence on athlete's perception of their performance. Klotzbier and Schott tested novice and experienced gymnasts and soccer players with different perceptual task (recognition of soccer-specific poses) and with mental rotation tasks using different stimuli (soccer-specific poses, cubes, line-drawings of hands, letters). Their results suggest that gymnasts' motor expertise plays a role in their performance on mental rotation tasks involving both egocentric and object-based transformations, regardless of the stimuli presented. For learning a three-ball juggling cascade, Geller et al. compare a "learning-in-parts" training regime (gradually increasing difficulty) and elements of the juggling movement to an "all-at-once" regime (training on the complete skill from the start). They report initial advantages of the all-at-once group, but no difference in performance between the groups at the end of the training sessions.

This Research Topic thereby enables valuable, current, conceptual as well as empirical insights into cognitive-motor research.

Author contributions

SS: Writing – original draft, Writing – review & editing. KZ: Writing – original draft, Writing – review & editing. KS: Writing – original draft, Writing – review & editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 11 October 2022
DOI 10.3389/fpsyg.2022.945389

Check for updates

OPEN ACCESS

EDITED BY
Kylie Ann Steel,
Western Sydney University, Australia

REVIEWED BY
Ana Ramos,
University of Porto, Portugal
Pablo Juan Greco,
Federal University of Minas Gerais,
Brazil

*CORRESPONDENCE
Andre Nicklas
a.nicklas@dshs-koeln.de

SPECIALTY SECTION
This article was submitted to
Movement Science and Sport
Psychology,
a section of the journal
Frontiers in Psychology

RECEIVED 16 May 2022
ACCEPTED 13 September 2022
PUBLISHED 11 October 2022

CITATION
Nicklas A, Rückel L-M, Noël B,
Varga M, Kleinert J, Boss M and Klatt S
(2022) Gaze behavior in social
interactions between beach volleyball
players—An exploratory approach.
Front. Psychol. 13:945389.
doi: 10.3389/fpsyg.2022.945389

Gaze behavior in social interactions between beach volleyball players—An exploratory approach

Andre Nicklas[1]*, Lisa-Marie Rückel[1], Benjamin Noël[1], Matyas Varga[2,3], Jens Kleinert[4], Martin Boss[4] and Stefanie Klatt[1,2]

[1]Institute of Exercise Training, Sport Informatics, Department of Cognitive and Team/Racket Sport Research, German Sport University Cologne, Cologne, Germany, [2]Sport and Exercise Science and Medicine Research Group, University of Brighton, Brighton, United Kingdom, [3]School of Sport, Exercise, and Health Sciences, Loughborough University, Loughborough, United Kingdom, [4]Institute of Psychology, Department of Health and Social Psychology, German Sport University Cologne, Cologne, Germany

Previous research has indicated that social interactions and gaze behavior analyses in a group setting could be essential tools in accomplishing group objectives. However, only a few studies have examined the impact of social interactions on group dynamics in team sports and their influence on team performance. This study aimed to investigate the effects of game performance pressure on the gaze behavior within social interactions between beach volleyball players during game-like situations. Therefore, 18 expert beach volleyball players conducted a high and a low game performance pressure condition while wearing an eye tracking system. The results indicate that higher game performance pressure leads to more and longer fixation on teammates' faces. A higher need for communication without misunderstandings could explain this adaptation. The longer and more frequent look at the face could improve the receiving of verbal and non-verbal information of the teammate's face. Further, players showed inter-individual strategies to cope with high game performance pressure regarding their gaze behavior, for example, increasing the number of fixations and the fixation duration on the teammate's face. Thereby, this study opens a new avenue for research on social interaction and how it is influenced in/through sport.

KEYWORDS

gaze behavior, social interaction, team sports, beach volleyball, game performance pressure

Introduction

People coordinate their abilities and skills over time and space in various tasks (e.g., passing a ball or building a house) to achieve a common goal (Fasold et al., 2021). Successful collaborations depend on various factors, such as visual and somatosensory information (Sebanz et al., 2006). Previous studies have shown that individuals can anticipate and integrate their partner's behavior in their own action planning by sharing mental representations of the expected outcome (Knoblich and Jordan, 2002; Jordan and Knoblich, 2004; Marsh et al., 2006). Clark and Krych (2004) showed that instructing another person on how to build a Lego model while seeing the working area leads to fewer errors and less time to finish. In a team sport context, for example, referees coordinate their gaze to officiate the game (Fasold et al., 2021), or players collaborate to score a goal (Klatt et al., 2021b). On a theoretical level, this is called joint action, which can be regarded as any form of social interaction (Sebanz et al., 2006; Knoblich and Sebanz, 2008).

Social interactions are the interplay of auditory and visual cues and aim to exchange information between at least two people (Argyle and Cook, 1976; Gobel et al., 2015; Wolf et al., 2018). Moreover, not only information but also emotions (e.g., anxiety, happiness) can be transferred implicitly or explicitly within social interactions (Hatfield et al., 2014). Notably, individuals with good interpersonal relationships are often likely to adapt to the collective emotions of the group (Tamminen et al., 2016). In the scientific literature, transferring emotions from one person to another is called emotional contagion (see Hatfield et al., 2014; Boss and Kleinert, 2015; Herrando and Constantinides, 2021; for a review). To exemplify, Moll et al. (2010) showed that post-performance emotions could be transferred to the teammates and influence the overall team performance. Specifically, authors found that celebrating a soccer kick with both arms raised increases the likelihood of the player's team winning the shootout. Another well-known phenomenon associated with emotional contagion is the collective team collapse, which describes a sudden performance drop of the entire team (Wergin et al., 2018). An important factor within this phenomenon is negative emotional contagion. Experiencing negative emotions is associated with individual underperformance (Barsade and Gibson, 2012; Hill and Shaw, 2013). So, negative emotional contagion can lead to more teammates that underperform. For example, player A might feel insecure or anxious after making a mistake. These negative emotions can be transferred to another teammate (Herrando and Constantinides, 2021 for a review) and affect the teammate's performance. Thus, the transmission of negative emotions can run through the whole team and lead to a collective team performance drop (Wergin et al., 2018).

In non-continuous sports, such as volleyball or tennis doubles, the nature of the game (e.g., breaks between the rallies) allows for a high frequency of social interactions between the teammates. That is why beach volleyball was chosen in this study. In addition, beach volleyball was chosen because there is no coach on the sidelines, which means that the players have to rely on each other for support and feedback. Notably, social interactions are usually not during the performance task itself. Regardless, the probability of emotional contagion with these frequent social interactions is critical for the subsequent team performance. This frequent and intense exchange of verbal and non-verbal information (e.g., instruction about the next play, emotions expressed by the body position) requires teammates to interpret these signals correctly and adjust their actions accordingly (Sebanz and Knoblich, 2009; Gweon and Saxe, 2013). For example, as mentioned above, player A might feel insecure after making a mistake. As a result, the teammates who have recognized player A's emotions may try to overcompensate for their teammates. By noticing the latent support, player A may focus on improving the current game rather than brooding over a past mistake, ultimately regaining security.

Gaze behavior plays an essential role in transmitting emotions within social interactions because of its dual functionality (Gobel et al., 2015). This means that the eyes send information to another person and at the same time receive signals from the interacting person (Gobel et al., 2015).

The information sent by the eyes depends on the gaze's direction (directed or averted) and duration and plays a crucial role in communication (Wirth et al., 2010; Canigueral and Hamilton, 2019). In detail, directed gaze refers to looking into somebody's face. It signals that the sender desires an interaction and expresses positive emotions such as joy, anger, or affection (Foulsham et al., 2011). Instead, averted gaze involves, for example, looking at the floor while communicating with another person. It indicates the person's unwillingness to communicate and represents negative emotions such as fear, worry, or shame (Argyle and Cook, 1976; Kleinke, 1986).

Previous research has shown that external stimuli such as stress or anxiety lead to gaze behavior changes as increased fixation on irrelevant stimuli and increased eye movement (Allsop and Gray, 2014; Vine et al., 2015). This is in line with the attentional control theory (ACT) (Corbetta and Shulman, 2002; Eysenck et al., 2007), which states that stress or anxiety is intended to reduce the relative influence of the top-down (goal-directed) system in favor of the bottom-up (stimulus-directed) system of attention. As a result, the individual's attention is no longer outwardly focused on goal-related sources of information and a performance decline can be expected (e.g., Wilson et al., 2009; Noël and Kamp, 2012). In addition, Herten et al. (2017) examined participants' gaze behavior in an interviewing situation and found shorter fixation durations on the face of interviewing committee members under a high-stress condition compared with a low-stress condition.

Despite the importance of social interactions in team sports and the crucial duality of the eye within this domain, studies dedicated to investigating social interaction in team sports context are scarce to date. Particularly, the examination of how gaze behavior is impacted by game performance pressure and whether inter-individual differences occur remains unclear in the literature. Indeed, so far most of the previous studies have focused on investigating the gaze behavior of individuals in their assigned tasks in a laboratory setting under varying stress conditions (e.g., Allsop and Gray, 2014; Allsop et al., 2016). A few studies have investigated the cooperative gaze behavior of teams in the laboratory (e.g., Bahrami et al., 2010; Neider et al., 2010), and an even smaller number have investigated the cooperative gaze behavior of groups in sports settings during the game (e.g., Fasold et al., 2018, 2021; Klatt et al., 2021a). Nevertheless, based on the dual function of the eyes, it seems reasonable that gaze behavior influences emotional contagion and, therefore, affects team performance. Thus, this study aimed to investigate gaze behavior in social interactions of expert beach volleyball teams in game-like situations and how it is affected by game performance pressure. Based on the literature, the study evaluates the hypothesis whether high game performance pressure lead to fewer fixations and shorter fixation durations (c.f., Allsop and Gray, 2014). Furthermore, shorter fixation durations on the teammates' faces are hypothesized (cf. Herten et al., 2017).

Materials and methods

Participants

A total of 18 participants (nine females and nine males) were included in this study. The following criteria were used to include the participants into the study: (1) active beach volleyball players competing at least at state level; (2) practicing for more than 6 h per week; (3) more than 1 year of competitive training; and (4) normal or corrected-to-normal vision. Participants included in the statistical analysis were four female (M_{age} = 16.00 years, SD_{age} = 0.00) and three male (M_{age} = 22.60 years; SD_{age} = 3.78) beach volleyball players. For the remaining 11 participants, fulfillment of at least one condition was insufficient for further data analysis (e.g., recorded frames per second were not 30 or the video file was corrupted). This was mainly caused due to the dynamic nature of beach volleyball. The athletes included in the statistical analyses were engaged in competitive training and games for at least 2 years preceding the experiment (M = 2.79 years, SD = 1.35). They trained on average for 12.84 h (SD = 4.58) per week. Two athletes were a part of the c-squad (regional level) at the time of data collection. All participants had previously participated in the German Championships in their respective age categories. More detailed information about the participants is listed in **Supplementary Table 1**. The study was in accordance with the principles outlined by the World Medical Association's Declaration of Helsinki and the Office of Research Ethics at the German Sport University Cologne (ethics proposal number: 184/2020). All participants and, if necessary, their legal guardians gave written consent to participate in this study voluntarily.

Design

The game performance pressure manipulation was conducted in two different beach volleyball game forms. The low game performance pressure condition consisted of a standard beach volleyball set of 21 points. In contrast, under the high game performance pressure condition, the participants played nine short sets starting at 17:17, reaching 21 points to win in a best-of-9 mode. This manipulation was based on the findings of Marcelino et al. (2011) and Ramos et al. (2020), who found that final set moments were considered as high-pressure moments. Due to the shorter set length and the associated greater importance of each error right at the beginning of the set under the high game performance pressure condition, this form of play implicitly increases the game performance pressure on the athletes.

Materials

The participants' gaze behavior was assessed using four binocular mobile eye tracking systems (Kassner et al., 2014). Each mobile bundle consisted of a mobile phone (Motorola Moto Z2/Z3 Play) and a Pupil Core Headset (Pupil Labs GmbH, Berlin, Germany). The gaze accuracy is stated as 0.60° and the gaze precision as 0.02° (Pupil Labs GmbH, Berlin, Germany). The eye tracking data were recorded using the pupil mobile app on the mobile phone and simultaneously streamed and recorded *via* a Wireless Router (AVM FRITZ!Box 7590 Router) to a notebook (Dell Latitude 3510, 16 GB RAM, Intel Core i7), using the pupil capture app running on Windows 10. The routers were connected to the laptop *via* a LAN cable. Two eye tracking systems were streamed *via* the same router onto a notebook. Thus, two routers and two laptops were used. The eye tracking video was recorded with 30 frames per second.

Procedure

Before participating in the experiment, participants warmed up as they would do before a competition, followed by a familiarization task wearing the eye tracking device. The familiarization task consisted of eight rallies including four side-out situations for each team. In the side-out situation, the opposing team serves. The own team has to receive the serve and set the ball and then attack. After the familiarization task, the participants took part in the two game performance pressure conditions (low vs. high) in a counterbalanced order. Thus, half of the teams started with the low and the other half with the high game performance pressure condition. Between these conditions, participants took a 10-min break. Before each game performance pressure condition, a *Manual Marker Calibration* (Kassner et al., 2014) was conducted: The participants stood in the middle of the beach volleyball court, while one examiner held a Pupil Calibration Marker v0.4 in his hands and stood one meter away from them. The participants were told to follow the Pupil Calibration Marker v0.4 with their eyes and not to move their heads, while the examiner followed a pre-defined route with the marker. After seven points, the participants also conducted a short in-game calibration instead of changing sides. Therefore, the participants stood in front of a Pupil Calibration Marker v0.4 placed on the side of their court. Participants focused their gaze on the midpoint of the marker while moving their heads up and down as well as to the left and right. One week prior to the testing, the *Team Cohesion Questionnaire [Fragebogen zur Mannschaftskohäsion]*[1] (Lau et al., 2003) and the expertise questionnaire were sent to be filled out by the participants until the day of the testing. The Team Cohesion Questionnaire was used to control for the possible influence of different relationship levels between team members on the study's results. This is necessary because emotions are more easily transferred between team members with a good relationship than between team members with a poor relationship (cf. Tamminen et al., 2016). The expertise questionnaire only consisted of questions to ensure that the participants fulfilled the inclusion criteria.

Data extraction

Social interactions between the rallies were tagged in the eye tracking videos (startpoint and endpoint were marked in the video). The starting point of the social interaction began when the previous rally was completed (the ball touched the ground) and ended when the teammates moved away from each other again to take their positions for the next rally. Thereafter, manual frame-by-frame analysis was used to analyze the athletes' gaze behavior within these social interactions. This method has been successfully used by various researchers in previous investigations (see Patla and Vickers, 2003; Klatt et al., 2021a). We defined fixation as a gaze on the same area of interest (AOI: *face, upper body, lower body, and environment*) for more than 100 ms (more than three following frames) irrespective of these AOI moving in space (see Causer et al., 2010; Panuk et al., 2017). The AOI face, upper body, and lower body were defined as the teammate's corresponding body parts. The AOI environment covered all other possible fixation points.

Data analysis

We conducted a repeated measures MANOVA using Pillai's Trace with game performance pressure level (low, high) as within-subject factor, participants (1–7) as between-subject factor, and the number of fixations as well as fixation duration on the areas of interest (*face, upper body, lower body, environment*) as dependent variables. In case of any multivariate effects, subsequent univariate tests were conducted. Greenhouse–Geisser adjustment was used to correct for violations of sphericity (if necessary) (O'Brien and Kaiser, 1985). For all tests, an alpha level was set at 0.05 and for effect size estimation eta square was used. A small effect was assumed for $\eta^2 = 0.01$, a medium effect for $\eta^2 = 0.06$, and a large effect for $\eta^2 = 0.14$ (Cohen, 1988). The calculation was done using SPSS (version 28).

Results

The mixed MANOVA showed multivariate significant effects of game performance pressure level [*Pillai's Trace* = 0.09, $F(8,192) = 2.43$, $p = 0.016$, $\eta^2 = 0.014$], participants [*Pillai's Trace* = 0.84, $F(48,1182) = 4.02$, $p < 0.001$, $\eta^2 = 0.14$] as well as the game performance pressure level * participants interaction [*Pillai's Trace* = 0.44, $F(48,1182) = 1.97$, $p < 0.001$, $\eta^2 = 0.07$].

Game performance pressure level: Subsequent univariant analyses showed that the game performance pressure level had a significant effect on fixation duration on the face [$F(1,199) = 7.02$, $p = 0.009$, $\eta^2 = 0.03$], the upper body [$F(1,199) = 6.06$, $p = 0.015$, $\eta^2 = 0.03$], and the number of fixations on the face [$F(1,199) = 10.36$, $p = 0.002$, $\eta^2 = 0.05$]. Under the high game performance pressure condition, participants fixated longer on the face and upper body (all *ps* < 0.05). Furthermore, the participants looked more frequently on the face ($p < 0.05$). All other univariate analyses did not show significant differences between the game performance pressure levels. All the means and standard deviation are shown in **Table 1**.

Participants: Univariate analyses showed that fixation duration on the team member's face [$F(6,199) = 4.27$, $p < 0.001$, $\eta^2 = 0.11$], upper body [$F(6,199) = 4.69$, $p < 0.001$, $\eta^2 = 0.12$], lower body [$F(6,199) = 4.17$, $p < 0.001$, $\eta^2 = 0.11$], and the environment [$F(6,199) = 5.44$, $p < 0.001$, $\eta^2 = 0.14$] differed statistically significant between the participants. The face fixation duration was significantly longer for participant 5 than for participant 4 ($p < 0.001$). For the upper body, participant 2 focused longer than participants 1, 3, and 7 (all *ps* < 0.05). Participant 6 fixated significantly longer on the

1 For reliability analysis, Cronbach's alpha was calculated and showed satisfying results of the social cohesion (0.84) and the task cohesion (0.81) (Lau et al., 2003). The average retest reliability coefficient for these subscales is rtt = 0.73 and the average intercorrelation is $r = 0.54$ (Lau, 2005).

TABLE 1 Means and standard deviation of the fixation durations and numbers of fixations on the AOI face, upper body, lower body, and environment in relation to the game performance pressure condition.

	Fixation duration [ms]				*Number of fixations*			
	High game performance pressure		*Low game performance pressure*		*High game performance pressure*		*Low game performance pressure*	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Face	315.01	493.39	199.35	375.32	0.61	0.78	0.42	0.60
Upper body	447.25	447.21	383.82	443.51	0.82	0.71	0.76	0.73
Lower body	51.78	207.38	37.86	147.36	0.09	0.32	0.09	0.331
Environment	1978.32	2447.03	1583.82	2192.75	1.14	0.79	1.05	0.87

teammate's lower body in social interaction than participants 2, 3, and 7 (all *ps* < 0.005). Participants 2, 3, and 6 spent significantly less time on the environment than participants 4 and 7. For a graphical overview, the different fixation durations of the participants are shown in **Figure 1**. All the means and standard deviation are shown in **Table 2**.

For the number of fixations, the univariate tests revealed significant differences between participants' fixations on the face [F(6,199) = 2.59, $p = 0.019$, $\eta^2 = 0.07$], on the upper body [F(6,199) = 6.77, $p < 0.001$, $\eta^2 = 0.17$], on the lower body [F(6,199) = 4.15, $p < 0.001$, $\eta^2 = 0.11$], and on the environment [F(6,199) = 5.67, $p = 0.001$, $\eta^2 = 0.15$]. Participant 4 fixated on the teammate's face significantly more often than participant 5 ($p = 0.028$). On the teammate's upper body, participant 3 showed significantly fewer fixations than participants 2, 4, 5, and 6 (all *ps* < 0.05). Also, in contrast to participant 7, participants 4 and 5 focused on the upper body significantly more often. Participants 3 fixated on the lower body in social interaction significantly less often than participants 4 and 6 (all *ps* < 0.05). For the number of fixations on the environment, there was a significantly lower number for participants 2 and 3 compared with participants 4 and 5 (all *ps* < 0.05). In addition, participant 3 had lower fixation numbers than participant 1 ($p < 0.001$) (see **Figure 2**). All the means and standard deviation are shown in **Table 3**.

*Game performance pressure level * Participants interaction:* The univariate analyses of the interaction between the participants and game performance pressure level showed that the level of game performance pressure affected participants' gaze differently with regard to upper body fixation durations [F(6,199) = 2.86, $p = 0.011$, $\eta^2 = 0.08$] and fixation durations of the environment [F(6,199) = 5.00, $p < 0.001$, $\eta^2 = 0.13$]. Participants 1, 4, and 5 spent less time focusing on the upper body under the high game performance pressure condition. In contrast, all others looked longer at their partner's upper body under the high game performance pressure condition. Considering the fixation durations, only participants 1 and 2 focused for a shorter duration due to increased game performance pressure. These individual differences are shown in **Figure 3**. All other univariate analyses did not show significant differences between the game performance pressure levels (all *ps* > 0.05).

For the number of fixations, game performance pressure level * participant interaction indicated significant differences for the AOI face [F(6,199) = 2.70, $p = 0.015$, $\eta^2 = 0.07$] and environment [F(6,199) = 2.73, $p = 0.014$, $\eta^2 = 0.08$]. All but participant 1 fixated more often on the face under the high game performance pressure condition. Considering the AOI environment, only participants 1 and 5 showed a reduced frequency under the high game performance pressure condition. While this is the case, a reduction in the variance of fixation count can also be observed (see **Figure 4**).

Results Team Cohesion Questionnaire: The task cohesion ($M = 5.84$, $SD = 0.38$) and social cohesion ($M = 5.37$, $SD = 0.80$) values were high with slight variances. Despite the homogeneously high values, the female participants showed descriptively slightly higher values than the male participants (see **Supplementary Table 2**).

Discussion

This exploratory study aimed to examine whether a higher game performance pressure level leads to increased eye movements and shorter fixation durations in the social interaction between players between the rallies. The results showed that participants fixate significantly longer on the upper body and the face under the high game performance pressure conditions. Further, the participants looked more frequent at their teammates' faces. No other changes in gaze behavior were found due to game performance pressure level manipulation. The analysis also showed that there are individual differences between the participants.

Concerning the longer and more frequent fixation on the teammates' faces and longer duration on the teammates' upper body under the high game performance pressure condition, it seems that especially the face takes on a special role within

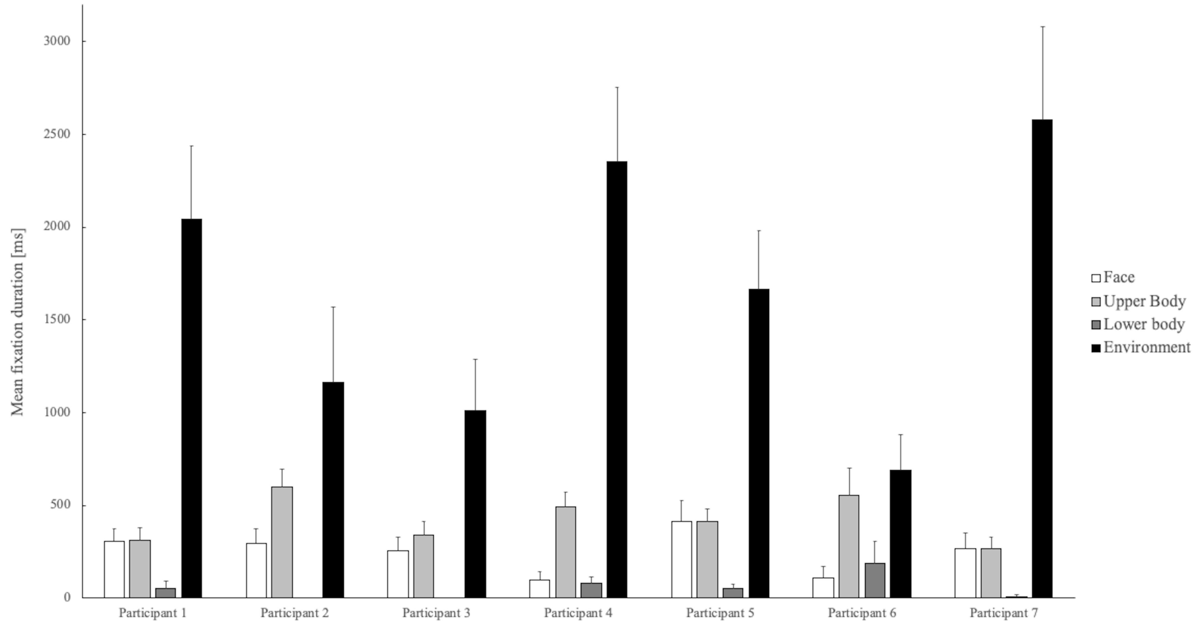


FIGURE 1
Mean fixation time of the players on the different areas of interest in ms. The error bars indicate the respective standard errors.

TABLE 2 Means and standard deviation of the fixation durations of the participants on the AOI face, upper body, lower body, and environment included in the statistical analysis.

	Fixation duration [ms]							
	Face		Upper body		Lower body		Environment	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Participant 1	304.76	410.04	311.43	397.37	54.76	238.23	2042.38	2347.99
Participant 2	292.97	433.08	601.15	499.80	0.00	0.00	1164.94	2180.75
Participant 3	258.05	375.50	342.53	381.29	0.00	0.00	1009.77	1496.12
Participant 4	97.97	297.89	495.12	504.30	81.71	212.44	2356.10	2566.96
Participant 5	416.15	622.65	413.54	368.84	51.04	151.10	1665.63	1803.19
Participant 6	110.61	202.91	554.55	487.59	189.39	388.48	692.42	627.244
Participant 7	268.39	440.35	265.52	342.04	8.62	65.65	2580.46	2703.26

the social interaction between the rallies. On the one hand, faces send a lot of emotional stimuli about the other person (Bahrick and Lickliter, 2014; Caulfield et al., 2016; Crivelli et al., 2016). Recognizing the emotions of the teammate is important to possibly provide support if the teammate needs it. However, it can also lead to emotion contagion, which may lead to a Collective Team Collapse, if negative emotions are transferred (Wergin et al., 2018). On the other hand, the visual system also plays a crucial role in the reception of auditory information (Klatt and Smeeton, 2020). For example, directing the gaze to the speaker improves the auditory stimulus reception (Dodd, 1977; Summerfield, 1987). Especially in tight game situations, understanding the verbal information of the teammate correctly seems to be decisive, as any loss of points can lead to defeat. Interestingly, individual differences in gaze behavior and success rate seem to indicate a pattern underlining this assumption. The players winning most of the rallies in this study (participants 5 and 6) increased the duration and number of fixations on the face under the high game performance pressure condition. In contrast, the player losing the most rallies in this study (participant 1) fixated the teammate's face less and for a shorter time. This could lead to the assumption that the pattern of participants 5 and 6 increases the quality of social interaction. This increased quality could be needed to generate better emotional and game-related feedback. In total, the better receiving of auditory information and teammate's

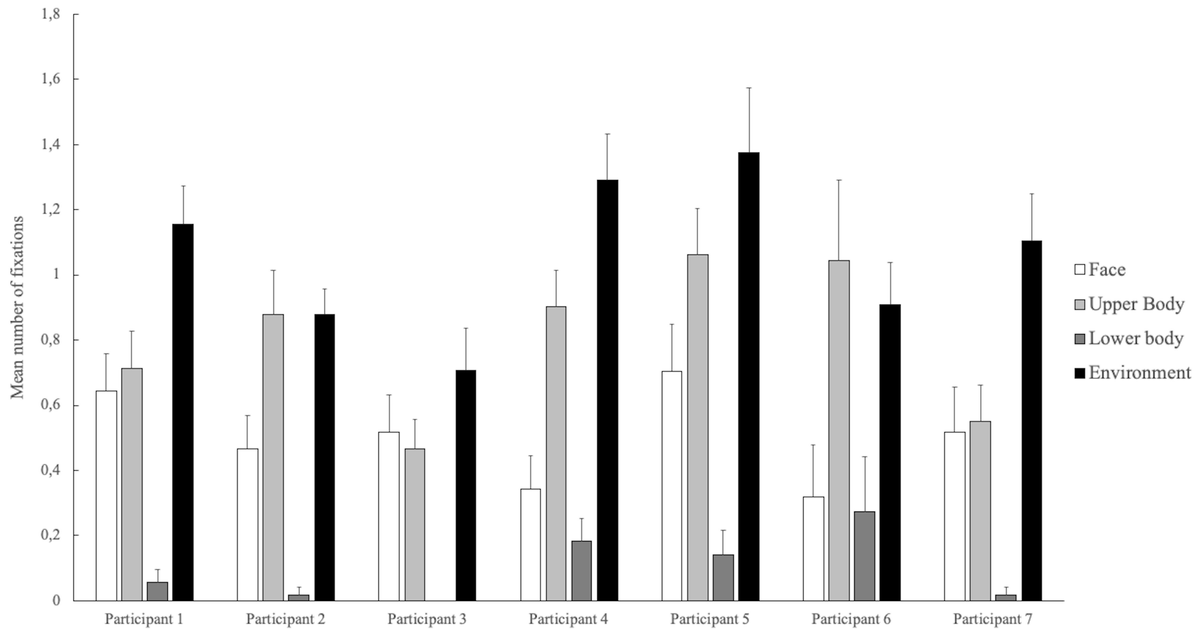


FIGURE 2
Mean fixation count on the different areas of interest for each player. The error bars indicate the respective standard errors.

TABLE 3 Means and standard deviation of the number of fixations of the participants on the AOIs face, upper body, lower body, and environment included in the statistical analysis.

	Number of fixations							
	Face		*Upper body*		*Lower body*		*Environment*	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Participant 1	0.64	0.69	0.71	0.67	0.06	0.23	1.16	0.69
Participant 2	0.47	0.56	0.88	0.73	0.02	0.13	0.88	0.42
Participant 3	0.52	0.61	0.47	0.48	0	0	0.71	0.70
Participant 4	0.34	0.66	0.90	0.72	0.18	0.45	1.29	0.90
Participant 5	0.70	0.82	1.06	0.80	0.14	0.43	1.38	1.14
Participant 6	0.32	0.53	1.05	0.82	0.27	0.56	0.91	0.43
Participant 7	0.52	0.75	0.55	0.60	0.02	0.13	1.10	0.79

emotional state suggest that the adaptation of gaze behavior has a functional role. However, these results contradict the previous research findings, which found that individuals tend to adopt an averted gaze behavior (less fixation on the face) in stressful interview situations (Herten et al., 2017). In this situation, faces may be perceived as aversive stimuli. Therefore, the gaze was shifted from the threatening input (Mogg and Bradley, 1998; Mogg et al., 2000; Wilson and MacLeod, 2003) and direct to different objects in the environment rather than the face of the pressure-inducing person (Herten et al., 2017). In beach volleyball teams, the partner should not be considered as an aversive stimulus. Instead, the teammates had to work as a team toward a common goal, which differs from the interview situations investigated by Herten et al. (2017). **Supplementary Table 2** also emphasizes that the teammates are not considered as an aversive stimulus by showing that all teams had positive relationships. These findings indicate that compared with a situation where the other person is regarded as an aversive stimulus and face fixations are reduced, in a teamwork scenario, participants increase their duration and frequency of fixations on the partner's face to try and achieve better results.

According to the inter-individual difference, the results indicate that gaze behavior in social interaction is also affected by factors such as personality traits and socializing. Hence, in this study players showed inter-individual strategies to cope with the high game performance pressure condition regarding their gaze

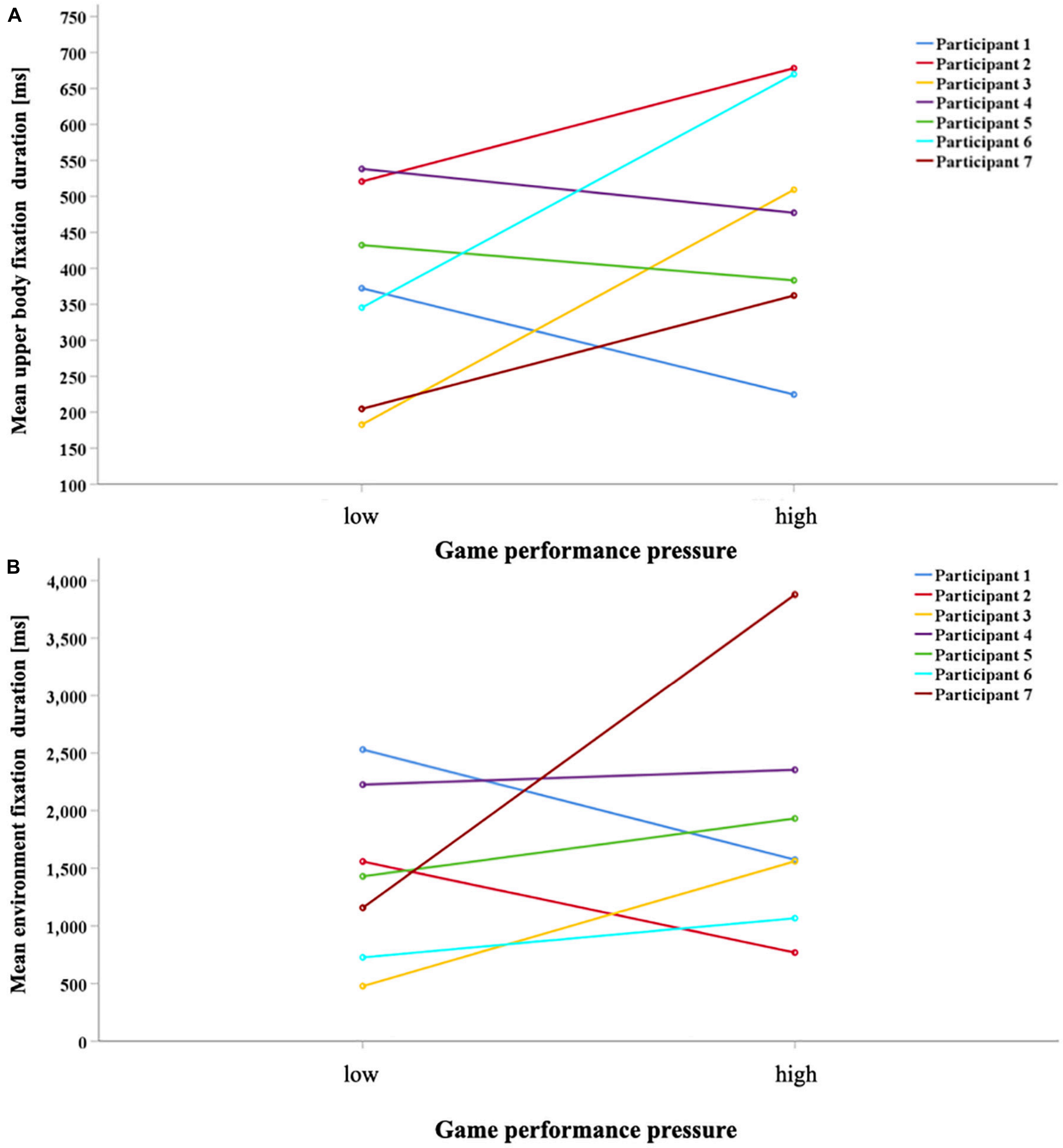


FIGURE 3
Each participant's mean fixation duration depending on the stress level on the upper body **(A)** and the environment **(B)**.

behavior. Notably, participant 5 had a distinct pattern of change in gaze behavior due to increased game performance pressure compared with other players. Participant 5 had a reduction in the total number of fixations, but an increased number and duration of fixations on the face. These results suggest that participant 5 became more focused on her teammate, allowing for emotional feedback and communication to occur more often and for longer than under the low-stress condition. In contrast to this strategy, participant 1 had decreased face fixation numbers and duration under the high game performance pressure condition. The changes in gaze behavior of participant 1 may have been the result of poor performance, which is emphasized by the lowest percentage of subsequent rallies won (34%) under the high game performance pressure condition. Due to this poor performance, it is possible that participant 1 averted his gaze caused by his own emotions such as fear or worry of making the next mistake (see Adams and Kleck, 2005). The teammate (participant 3) showed no significant changes in gaze behavior, assuming that these emotions were not transferred. So far, most studies have focused on mean group values, but not on individual differences (e.g., Herten et al., 2017; Timmis et al., 2018). However, it must be mentioned that the participants measured in this exploratory study were young competitive athletes, but not elite athletes. It could be that

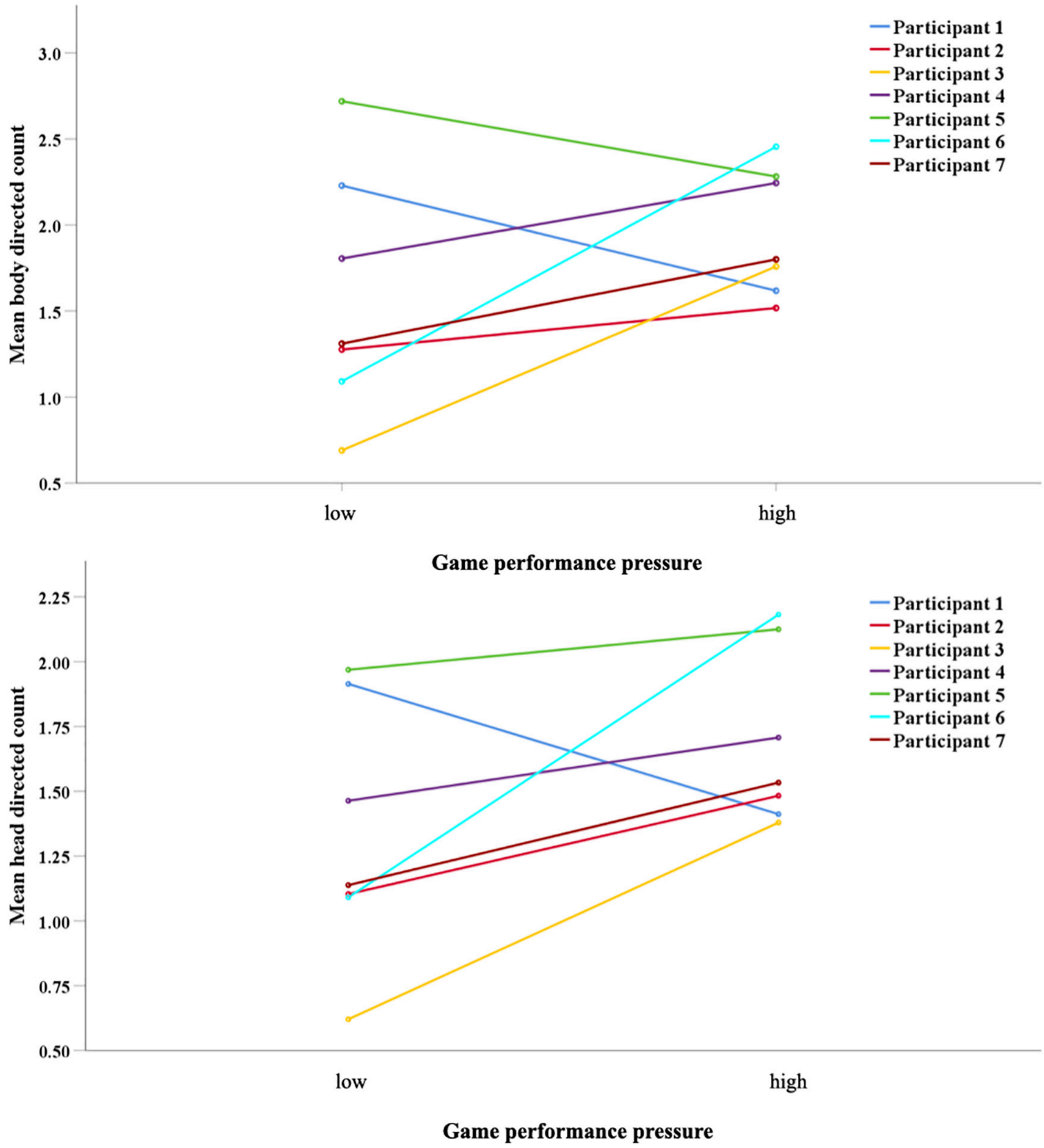


FIGURE 4
Mean fixation numbers on the face **(A)** and the environment **(B)** per participant for the high- and low game performance pressure condition.

elite athletes have a higher experience with game performance pressure and may adapt their gaze differently. Future research should therefore focus on the analysis of individual differences in gaze behavior in social interactions and in sport with a specific focus on elite athletes (see Dicks et al., 2016).

Conclusion

The study suggests a common change in gaze behavior in beach volleyball teams due to increased game performance pressure. An increased number and duration of fixations on the partner's face were found, possibly seeking emotional and game-related feedback, indicating the need for more frequent and prolonged interactions. Furthermore, longer fixation duration and higher numbers of fixations on the face could also have a functional role in the communication between the teammates.

In practice, coaches may want to encourage players to increase the quantity and quality (directed head and fixations on the face) of social interactions between the rallies. Improved social interaction could lead to earlier recognition of negative emotions of the teammate, and counteracting this can make the occurrence of a collective team collapse less likely. Routines can increase the quantity of gaze on the face of the teammate between the rallies, such as the athletes high-fiving each other and then having to look at each other's faces regardless of how the last rally went. Another way could be to inform the players about how important it is to gather the information sent by the teammate's face. Furthermore, verbal and non-verbal communication seems to be a crucial aspect to consider when forming a beach volleyball team.

It needs to be mentioned that the results of the current study are mainly exploratory and only traced back to a small sample size, which restricts the generalization of these findings. Moreover, it can be assumed that manipulating the game performance pressure level in this controlled setting is not comparable to game performance pressure during real competitions. It is possible that the players communicate differently in this experimental setting than they would in a game with spectators. Therefore, further research is needed to understand how gaze behavior changes due to stressful situations in social interactions in natural sport settings. It also seems to make sense to focus on phases of the game where social interaction is possible for a longer period, like time-outs, rather than only between the rallies. Nevertheless, this study opens the door to a new research field and raises new research topics within this area.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Office of Research Ethics German Sport University Cologne. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

L-MR, JK, MB, BN, and SK conceptualized the project. AN wrote the first draft of the manuscript and conducted the data recordings. MV analyzed the data. SK, MB, and BN revised all drafts and wrote parts of the manuscript. All authors contributed to the article and approved the submitted version.

Funding

This study was funded by the Federal Institute of Sports Science (Bundesinstitut für Sportwissenschaft, ZMVI4-072009/20).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.945389/full#supplementary-material

SUPPLEMENTARY FIGURE 1
Mean numbers of fixations for each AOI. Significant Wilcoxon's test results ($p < 0.013$) comparing the low- and high-stress conditions. Error bars represent the standard errors of the means.

SUPPLEMENTARY FIGURE 2
Mean total number of fixations for each AOI. Significant Wilcoxon's test results ($p < 0.01$) comparing the low- and high-stress conditions. Error bars represent the standard errors of the means.

References

Adams, R. B. Jr., and Kleck, R. E. (2005). Effects of direct and averted gaze on the perception of facially communicated emotion. *Emotion* 5, 3–11. doi: 10.1037/1528-3542.5.1.3

Allsop, J., and Gray, R. (2014). Flying under pressusre: Effects of anxiety on attention and gaze behavior in aviation. *J. Appl. Res. Memory Cogn.* 3, 63–71. doi: 10.1016/j.jarmac.2014.04.010

Allsop, J., Gray, R., Bulthoff, H. H., and And Chuang, L. (2016). Effects of anxiety and cognitive load on instrument scanning behavior in a flight simulation. *IEEE Second Workshop Eye Track. Visualiz.* 2016, 55–59. doi: 10.1109/ETVIS.2016.7851167

Argyle, M., and Cook, M. (1976). *Gaze and Mutual Gaze*. Cambridge: Cambridge University Press.

Bahrami, B., Olsen, K., Latham, P. E., Roepstorff, A., Rees, G., and Frith, C. D. (2010). Optimally interacting minds. *Science* 329, 1081–1085. doi: 10.1126/science.1185718

Bahrick, L. E., and Lickliter, R. (2014). Learning to attend selectively: The dual role of intersensory redundancy. *Current Directions In Psychological Science* 23, 414–420. doi: 10.1177/0963721414549187

Barsade, S. G., and Gibson, D. E. (2012). Group affect: Its influence on individual and group outcomes. *Curr. Direct. Psychol. Sci.* 21, 119–123. doi: 10.1177/0963721412438352

Boss, M., and Kleinert, J. (2015). Explaining social contagion in sport applying Heider's balance theory: first experimental results. *Psychol. Sport Exerc.* 16, 160–169. doi: 10.1016/j.psychsport.2014.10.006

Canigueral, R., and Hamilton, A. F. C. (2019). The role of eye gaze during natural social interactions in typical and autistic people. *Front. Psychol.* 10:560. doi: 10.3389/fpsyg.2019.00560

Caulfield, F., Ewing, L., Bank, S., and Rhodes, G. (2016). Judging trustworthiness from faces: Emotion cues modulate trustworthiness judgments in young children. *Br. J. Psychol.* 107, 503–518. doi: 10.1111/bjop.12156

Causer, J., Bennett, S. J., Holmes, P. S., Janelle, C. M., and Williams, A. M. (2010). Quiet eye duration and gun motion in elite shotgun shooting. *Med. Sci. Sports Exerc.* 42, 1599–1608. doi: 10.1249/MSS.0b013e3181d1b059

Clark, H. H., and Krych, M. A. (2004). Speaking while monitoring addressees for understanding. *J. Memory Lang.* 50, 62–81. doi: 10.1016/j.jml.2003.08.004

Cohen, J. (1988). "Chapter 8. the analysis of variance and covariance," in *Statistical Power Analysis For The Behavioral Sciences*, (New York: Routledge Academic), 273–406. doi: 10.1016/B978-0-12-179060-8.50013-X

Corbetta, M., and Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nat. Rev. Neurosci.* 3, 201–215. doi: 10.1038/nrn755

Crivelli, C., Jarillo, S., Russell, J. A., and Fernández-Dols, J.-M. (2016). Reading emotions from faces in two indigenous societies. *J. Exp. Psychol. General* 145, 830–843. doi: 10.1037/xge0000172

Dicks, M., Button, C., Davids, K., Chow, J. Y., and Der Kamp, J. (2016). Keeping an eye on noisy movements: On different approaches to perceptual-motor skill research and training. *Sports Med.* 47, 575–581. doi: 10.1007/s40279-016-0600-3

Dodd, B. (1977). The role of vision in the perception of speech. *Perception* 6, 31–40. doi: 10.1068/p060031

Eysenck, M. W., Derakshan, N., Santos, R., and Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion* 7:336. doi: 10.1037/1528-3542.7.2.336

Fasold, F., Nicklas, A., Seifriz, F., Schul, K., Noël, B., Aschendorf, P., et al. (2021). Gaze coordination of groups in dynamic events–a tool to facilitate analyses of simultaneous gazes within a team. *Front. Psychol.* 12:816. doi: 10.3389/fpsyg.2021.656388

Fasold, F., Noël, B., Wolf, F., and Hüttermann, S. (2018). Coordinated gaze behaviour of handball referees: A practical exploration with focus on the methodical implementation. *Mov. Sport Sci. Sci. Motric.* 2018, 71–79. doi: 10.1051/sm/2018029

Foulsham, T., Walker, E., and Kingstone, A. (2011). The where, what and when of gaze allocation in the lab and the natural environment. *Vision Res.* 51, 1920–1931. doi: 10.1016/j.visres.2011.07.002

Gobel, M. S., Kim, H. S., and Richardson, D. C. (2015). The dual function of social gaze. *Cognition* 136, 359–364. doi: 10.1016/j.cognition.2014.11.040

Gweon, H., and Saxe, R. (2013). "Developmental cognitive neuroscience of theory of mind," in *Neural circuit development and function in the brain*, Vol. 3, eds J. L. R. Rubenstein and P. Rakic (Amsterdam: Elsevier), 367–377. doi: 10.1016/B978-0-12-397267-5.00057-1

Hatfield, E., Bensman, L., Thornton, P. D., and Rapson, R. L. (2014). New perspectives on emotional contagion: A review of classic and recent research on facial mimicry and contagion. *Int. Int. J. Personal Relations.* 8, 159–179. doi: 10.5964/ijpr.v8i2.162

Herrando, C., and Constantinides, E. (2021). Emotional contagion: A brief overview and future directions. *Front. Psychol.* 2021:12. doi: 10.3389/fpsyg.2021.712606

Herten, N., Otto, T., and Wolf, O. T. (2017). The role of eye fixation in memory enhancement under stress - an eye tracking study. *Neurobiol. Learn. Mem.* 140, 134–144. doi: 10.1016/j.nlm.2017.02.016

Hill, D. M., and Shaw, G. (2013). A qualitative examination of choking under pressure in team sport. *Psychol. Sport Exerc.* 14, 103–110. doi: 10.1016/j.psychsport.2012.07.008

Jordan, J. S., and Knoblich, G. (2004). Spatial perception and control. *Psychon. Bull. Rev.* 11, 54–59. doi: 10.3758/BF03206460

Kassner, M., Patera, W., and Bulling, A. (2014). "Pupil: An open source platform for pervasive eye tracking and mobile gaze-based interaction," in *Proceedings Of The 2014 Acm International Joint Conference On Pervasive And Ubiquitous Computing: Adjunct Publication*, 1151–1160. doi: 10.1145/2638728.2641695

Klatt, S., Noël, B., Nicklas, A., Schul, K., Seifriz, F., Schwarting, A., et al. (2021a). Gaze behavior and positioning of referee teams during three-point shots in basketball. *Appl. Sci.* 11:6648. doi: 10.3390/app11146648

Klatt, S., Noël, B., Schwarting, A., Heckmann, L., and Fasold, F. (2021b). Adaptive gaze behavior and decision making of penalty corner strikers in field hockey. *Front. Psychol.* 12:674513. doi: 10.3389/fpsyg.2021.674511

Klatt, S., and Smeeton, N. J. (2020). Visual auditory information during decision making in sport. *J. Sport Exerc. Psychol.* 42, 15–25. doi: 10.1123/jsep.2019-0107

Kleinke, C. L. (1986). Gaze eye contact: A research review. *Psychol. Bull.* 100:78. doi: 10.1037/0033-2909.100.1.78

Knoblich, G., and Jordan, J. S. (2002). The mirror system joint action. *Adv. Consciou. Res.* 42, 115–124. doi: 10.1075/aicr.42.10kno

Knoblich, G., and Sebanz, N. (2008). Evolving intentions for social interaction: From entrainment to joint action. *Philos. Trans. R. Soc. Biol. Sci.* 363, 2021–2031. doi: 10.1098/rstb.2008.0006

Lau, A., Stoll, O., and Hoffmann, A. (2003). Diagnostik und stabilität der mannschaftskohäsion in den sportspielen. *Leipziger Sportwissenschaftliche Beiträge* 44, 1–24.

Lau, A. (2005). Das teamentwicklungstraining – ein systemisches konzept für die mannschaftssportspiele. *Leipziger Sportwissenschaftliche Beiträge* 46, 64–82.

Marcelino, R., Mesquita, I., and Sampaio, J. (2011). Effects of quality of opposition match status on technical tactical performances in elite volleyball. *J. Sports Sci.* 29, 733–741. doi: 10.1080/02640414.2011.552516

Marsh, K. L., Richardson, M. J., Baron, R. M., and Schmidt, R. (2006). Contrasting approaches to perceiving acting with others. *Ecol. Psychol.* 18, 1–38. doi: 10.1207/s15326969eco1801_1

Mogg, K., and Bradley, B. P. (1998). A cognitive-motivational analysis of anxiety. *Behav. Res. Ther.* 36, 809–848. doi: 10.1016/S0005-7967(98)00063-1

Mogg, K., Mcnamara, J., Powys, M., Rawlinson, H., Seiffer, A., and Bradley, B. P. (2000). Selective attention to threat: A test of two cognitive models of anxiety. *Cogn. Emot.* 14, 375–399. doi: 10.1080/026999300378888

Moll, T., Jordet, G., and Pepping, G.-J. (2010). Emotional contagion in soccer penalty shootouts: Celebration of individual success is associated with ultimate team success. *J. Sports Sci.* 28, 983–992. doi: 10.1080/02640414.2010.484068

Neider, M. B., Chen, X., Dickinson, C. A., Brennan, S. E., and Zelinsky, G. J. (2010). Coordinating spatial referencing using shared gaze. *Psychon. Bull. Rev.* 17, 718–724. doi: 10.3758/PBR.17.5.718

Noël, B., and Kamp, J. V. D. (2012). Gaze behaviour during the soccer penalty kick: An investigation of the effects of strategy anxiety. *Int. J. Sport Psychol.* 43, 326–345.

O'Brien, R. G., and Kaiser, M. K. (1985). Manova method for analyzing repeated measures designs: An extensive primer. *Psychol. Bull.* 97:316. doi: 10.1037/0033-2909.97.2.316

Panuk, D., Vickers, J. N., and Hopkins, W. G. (2017). Quiet eye predicts goaltender success in deflected ice hockey shots. *Eur. J. Sport Sci.* 17, 93–99. doi: 10.1080/17461391.2016.1156160

Patla, A. E., and Vickers, J. N. (2003). How far ahead do we look when required to step on specific locations in the travel path during locomotion? *Exp. Brain Res.* 148, 133–138. doi: 10.1007/s00221-002-1246-y

Ramos, A., Coutinho, P., Ribeiro, J., Fernandes, O., Davids, K., and Mesquita, I. (2020). Increasing tactical complexity to enhance the synchronization of collective behaviours: An action-research study throughout a competitive volleyball season. *J. Sports Sci.* 38, 2611–2619. doi: 10.1080/02640414.2020.1794265

Sebanz, N., Bekkering, H., and Knoblich, G. (2006). Joint action: Bodies minds moving together. *Trends Cogn. Sci.* 10, 70–76. doi: 10.1016/j.tics.2005.12.009

Sebanz, N., and Knoblich, G. (2009). Prediction in joint action: What, when, and where. *Top. Cogn. Sci.* 1, 353–367. doi: 10.1111/j.1756-8765.2009.01024.x

Summerfield, Q. (1987). "Some preliminaries to a comprehensive account of audio-visual speech perception," in *The Psychology Of Lip Reading*, ed. H. Eye (Hillsdale, NJ: Lawrence Erlbaum Associates), 3–51.

Tamminen, K. A., Palmateer, T. M., Denton, M., Sabiston, C., Crocker, P. R. E., Eys, M., et al. (2016). Exploring emotions as social phenomena among canadian varsity athletes. *Psychol. Sport Exerc.* 27, 28–38. doi: 10.1016/j.psychsport.2016.07.010

Timmis, M. A., Piras, A., and Van Paridon, K. N. (2018). keep your eye on the ball: The impact of an anticipatory fixation during successful unsuccessful soccer penalty kicks. *Front. Psychol.* 9:2058. doi: 10.3389/fpsyg.2018.02058

Vine, S. J., Uiga, L., Lavric, A., Moore, L. J., Tsaneva-Atanasova, K., and Wilson, M. R. (2015). Individual reactions to stress predict performance during a critical aviation incident. *Anxiety Stress Coping Int. J.* 28, 467–477. doi: 10.1080/10615806.2014.986722

Wergin, V. V., Zimanyi, Z., Mesagno, C., and Beckmann, J. (2018). When suddenly nothing works anymore within a team - causes of collective sport team collapse. *Front. Psychol.* 9:2115. doi: 10.3389/fpsyg.2018.02115

Wilson, E., and MacLeod, C. (2003). Contrasting two accounts of anxiety-linked attentional bias: Selective attention to varying levels of stimulus threat intensity. *J. Abnormal Psychol.* 112:212. doi: 10.1037/0021-843X.112.2.212

Wilson, M. R., Wood, G., and Vine, S. J. (2009). Anxiety, attentional control, performance impairment in penalty kicks. *J. Sport Exerc. Psychol.* 31, 761–775. doi: 10.1123/jsep.31.6.761

Wirth, J. H., Sacco, D. F., Hugenberg, K., and Williams, K. D. (2010). Eye gaze as relational evaluation: Averted eye gaze leads to feelings of ostracism relational devaluation. *Personali. Soc. Psychol. Bull.* 36, 869–882. doi: 10.1177/0146167210370032

Wolf, D., Mittelberg, I., Rekittke, L.-M., Bhavsar, S., Zvyagintsev, M., Haeck, A., et al. (2018). Interpretation of social interactions: Functional imaging of cognitive-semiotic categories during naturalistic viewing. *Front. Hum. Neurosci.* 2018:12. doi: 10.3389/fnhum.2018.00296

frontiers | Frontiers in Psychology

TYPE Brief Research Report
PUBLISHED 23 January 2023
DOI 10.3389/fpsyg.2022.1026017

Check for updates

OPEN ACCESS

EDITED BY
Donatella Di Corrado,
Kore University of Enna, Italy

REVIEWED BY
Sabine Schaefer,
Saarland University,
Germany
Hansi Scharfen,
Nordic Science,
Germany

*CORRESPONDENCE
Simon Knöbel
✉ Simon.knoebel@uni-leipzig.de

SPECIALTY SECTION
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

RECEIVED 23 August 2022
ACCEPTED 05 December 2022
PUBLISHED 23 January 2023

CITATION
Knöbel S and Lautenbach F (2023) An assist for cognitive diagnostics in soccer (Part II): Development and validation of a task to measure working memory in a soccer-specific setting.
Front. Psychol. 13:1026017.
doi: 10.3389/fpsyg.2022.1026017

An assist for cognitive diagnostics in soccer (Part II): Development and validation of a task to measure working memory in a soccer-specific setting

Simon Knöbel[1,2]* and Franziska Lautenbach[2]

[1]Faculty of Sport Science, Chair of Sport Psychology, Leipzig University, Leipzig, Germany, [2]Sport Psychology, Institute of Sport Science, Humboldt-Universität zu Berlin, Berlin, Germany

Cognitive diagnostics is of increasing interest to researchers and practitioners in the context of talent identification and performance enhancement in professional soccer. Research addressing the relevance of cognitive skills for sports performance has been based on the cognitive component approach (i.e., general cognitive processes) and the expert performance approach (i.e., sport-specific cognitive processes). Following the aim to combine the strengths of both approaches, we have previously developed and validated tasks to measure inhibition and cognitive flexibility in a soccer-specific setting, including a soccer-specific motor response. In line with the broad consistency on three core executive functions, this further development of diagnosing executive functions is to be completed with a task for the assessment of working memory. For this purpose, 60 amateur players with a soccer experience of at least one competitive season (M_{age}=25.95, SD_{age}=4.59) first conducted a computer-based version of the *n*-back (3-back) task followed by a 3-back task that required a soccer-specific motor response (i.e., pass) performed in a soccer-specific setting (i.e., SoccerBot100). Results show good reliability for both tasks. With regard to convergent validity, significant correlations between the computerized and soccer-specific task could be determined in target trials for response time (r=0.446) and accuracy (r=0.401). Thus, the soccer-specific *n*-back task can be considered a potentially valid instrument for assessing working memory and potentially allows soccer clubs to diagnose the three core executive functions in a consistent soccer-specific setting.

KEYWORDS

executive functions, diagnostics, soccer performance, validity, talent development

Introduction

Given complex and multifaceted performance requirements in soccer, cognition can be a crucial factor to achieve and maintain peak performance. Due to the continuous development of the game with decreasing time and space for each player (Carling, 2010; Wallace and Norton, 2014), latest research addressed psychological skills including cognition to optimize performance (Söhnlein and Borgmann, 2018; Beavan et al., 2020). In this context, the core executive functions (EFs)—inhibition, cognitive flexibility, and working memory—are considered crucial for effective and goal-directed behavior (Diamond, 2013). Technological advances in the field of cognitive diagnostics and training, such as Footbonaut (Saal et al., 2015), Helix (Kittelberger, 2018), or the SoccerBot (Heilmann et al., 2021) provide new possibilities to assess cognition within (more) ecologically valid settings.

However, so far, examination of reliability and (ecological) validity of newly developed systems and the cognitive tasks implemented through those are still a limitation restricting cognitive diagnostics (Beavan, 2019; Lautenbach et al., 2022). Most cognitive tasks used for diagnostics in the applied field have neither been developed driven by theory nor have they been validated empirically (Memmert, 2019). Consequently, it remains unclear how cognition can be measured appropriately to enable conclusions for on-field performance (Van Maarseveen et al., 2018). In this context, previously used tasks often lack the coupling of perception and action because they did not require a sport-specific motor response (Farrow and Abernethy, 2003; Murr et al., 2018). In a recent meta-analysis, Kalén et al. (2021) emphasize the application of sport-specific stimuli and responses within cognitive diagnostics to detect expertise related differences.

We have already aimed to implement these requirements in two empirical studies (Musculus et al., 2022). We successfully adapted well-established computerized tasks (see cognitive component approach, Nougier et al., 1991) for inhibition (i.e., flanker task) and cognitive flexibility (i.e., number-letter task), and transferred them to a soccer-specific setting (i.e., SoccerBot360), including soccer-specific stimuli (i.e., soccer players for the soccer-specific inhibition task) and a soccer-specific motor response (i.e., passing the ball; see expert performance approach, Ericsson, 2003). In doing so, we combined the merits of relevant approaches in cognitive diagnostics in sports (for detailed description of both approaches, see Voss et al., 2010; Musculus et al., 2022). In order to complete the previously developed soccer-specific tasks[1] for inhibition and cognitive flexibility and thus, to cover all core EFs, the aim of this study is to develop and validate a task to measure soccer-specific working memory.

From a theoretical and an applied perspective, investigating working memory (also referred to as updating) is relevant for performance in sports. Especially in strategic sports such as soccer (e.g., Voss et al., 2010), players are confronted with a large amount of information that they have to process and take into account for the selection of their options (Verburgh et al., 2014). Working memory enables individuals to keep information in mind and retrieving this information in order to mentally work with it, even if it "no longer perceptually present" (Diamond, 2013, p. 142). In other words, working memory is the ability to constantly store and update information depending on its relevance to the given situation. Based on this definition, working memory and inhibition are closely linked and rarely occur independently of each other since constant mental retention of the goal is presumed for inhibitory performance (Diamond, 2013). Transferred to competitive soccer, the relevance of working memory results from constant processing and updating of retrieved information. Players must be able to adjust their behavior based on the information gathered and the comparison with previous experiences (Vestberg et al., 2012), for example, if an opponent repeatedly makes the same run or movement. In addition, the players have to keep in mind their tactical setup or instructions, as well as the behavior of their teammates, and adapt them in case of situational changes (Huijgen et al., 2015). Thus, in addition to inhibition and cognitive flexibility, the core EF working memory also have a potential impact on game performance and are thus, also relevant to assess from an applied perspective.

1 We initially addressed inhibition and cognitive flexibility, which formed the basis for further research (for details on the procedure and the development process see: Musculus et al., 2022).

The present study

In preparation for the study, we identified the *n*-back task (Kirchner, 1958) as a commonly used task to assess working memory capacities (Conway et al., 2005; see Supplementary Table 1A for justification based on previous studies). Additionally, the *n*-back task is highly practicable for the implementation in the SoccerBot due to the merely visual representation of the stimuli and the button press response in the computer task, in comparison to other tasks that require verbal responses (e.g., working memory span test, Conway et al., 2005; Scharfen and Memmert, 2021). At this point, it should be noted that other tasks are also used to assess working memory and correlation with soccer performance has been demonstrated (e.g., Backward Visual Memory Span, Huijgen et al., 2015; Corsi-block task, Scharfen and Memmert, 2019; and design fluency, Vestberg et al., 2017). However, the decision to use the *n*-back task is primarily, regardless of the soccer context, because it is a standard, frequently used and validated task to measure working memory (Kane et al., 2007, p. 615).

The study was conducted in accordance to our preceding soccer-specific task development and evaluation of inhibition and cognitive flexibility. Amateur soccer players performed both computerized and soccer-specific *n*-back tasks. Soccer-specific means that the tasks were conducted in a setting, in which participants were standing and responding to soccer-related stimuli (i.e., pictures of typical soccer actions) by executing soccer-specific responses, namely passing to goals (Musculus et al., 2022). This environment can be considered context-specific for the sample of amateur soccer players and thus, should increase ecological validity of the task (see review by Lumsden et al., 2016). However, while the selected images depict typical soccer actions, they do not represent situations based on which a decision or action must be made during a game. Since the study aims to assess the working memory performance of soccer players in combination with a soccer-specific motor response, the presentation of a representative game situation was less relevant than presenting clearly distinguishable stimuli in the sense of the original task.

We expected to find positive correlations with regard to response times and correct answers in the computer-based task and the soccer-specific task, indicating that the two tasks are related in terms of convergent validity and the soccer-specific tasks also allows for measuring working memory.

Additionally, we collected data on players' subjective perceptions of fun, stress, motivation, and physical exhaustion due to the tasks to control for potential confounders on cognitive performance. Thus, we asked the players about their physical exhaustion in order to monitor physical load of the participants before and during testing based on studies showing a decline in performance due to cognitive or physical fatigue (e.g., Smith et al., 2016). Along with this, we asked for perceived stress induced by the tasks, also to identify possible differences between the settings. Furthermore, we assessed motivation prior to the respective tasks as it is attributed a potential influence within cognitive diagnostics (Beavan et al., 2020; Vestberg et al., 2020). Finally, the perceived fun of the tasks was assessed based on the assumption that participants' engagement depends on the motivation and enjoyment elicited by the cognitive task (e.g., Lumsden et al., 2016). Accordingly, the engagement of the participants is an important characteristic of the quality of cognitive data collection (e.g., Walton et al., 2018).

Materials and methods

Participants

A total of 60 male soccer players ($M_{age} = 25.95$, $SD_{age} = 4.59$) participated in the study. Only adult players with a soccer experience of at least one competitive season in soccer were included to ensure basic soccer technical skills (see also Musculus et al., 2022). On average, participants had played soccer for 14.82 years ($SD = 6.03$) and practiced 4.07 h/week ($SD = 7.40$). Seven participants used to play in a youth academy when they were younger. Most players played in the seventh ($n = 17$) and sixth highest league in Germany ($n = 12$), followed by nine players in the eighth and seven in the ninth division. Further, three players played in the 10th highest, three in the fifth highest, two in the fourth highest, and one in the third highest league. Prior to participation, all players signed written informed consent. The study was carried out following the Declaration of Helsinki and approved by the ethics committee of Leipzig University (2020.11.17_eb_69).

Material

n-Back task

In the *n*-back task, participants see an emotional neutral stimuli (i.e., each presentation of a stimulus is referred to as a trial) and have to decide whether the same stimulus was presented *n* items before (Jaeggi et al., 2010, p. 394). Therefore, a button press response usually on a keyboard is only required if a so-called target trial is presented. If the stimulus *n* positions before does not match the current stimulus and it is therefore a non-target trial the participants should not react, meaning not to press a button or play a pass the ball in the SoccerBot. If a motor response is made to a non-target trial it represents a false alarm.

In the present study, the *n* was set to 3 based on research results that have shown that the 3-back task can be considered the most reliable (Hockey and Geffen, 2004). The main process measured is the updating ability of working memory, which involves the continuous assimilation of new information and the replacement of old information (Hockey and Geffen, 2004; Jaeggi et al., 2010). The collected data show whether and how often the *n*-back was recognized correctly (i.e., accuracy). Updating ability is then evaluated in combination with the required response time. High amount of correct responses and faster response times, represent better working memory (Kirchner, 1958). For the computerized task, stimuli were presented in the form of pictures with various neutral objects, such as a lamp, chair, or bicycle (see Figure 1A).

For the 3-back task developed and used in the SoccerBot100, setting, response, and stimuli were soccer-specific: Players were standing in a soccer field; they had to respond by passing a ball; and pictures of different soccer-related actions were presented as stimuli (see Figure 1B). Participants had to kick the ball into a goal that was constantly presented centered below the changing stimuli (Figure 1C). In case of a target trial, the players should react as quickly as possible with a pass into that goal.

Instruments to measure general and sport-specific working memory

To measure general working memory, we presented the computerized cognitive task on a 15-in. Laptop (1,280 × 960 pixels at 60 Hz) at a viewing distance of approximately 60 cm, using Inquisit 5 (2018). Participants were asked to press the key "A" only responding to target trials and not reacting to non-target trials.

Similar to the previous tasks assessing inhibition and cognitive flexibility, the development of the soccer-specific 3-back task was accomplished in collaboration with sport psychologists and sport scientists of a German first division soccer club as well as the Umbrella Software Company. Programmers of the latter institution then implemented this task for the SoccerBot100. The SoccerBot100 is a smaller version of the SoccerBot360 with a smaller field (i.e., artificial grass area) but with walls for projections (for a more detailed description see Supplementary material). In both tasks, participants performed two consecutive experimental blocks. Both blocks of the 3-back task consisted of 50 trials (see justification in Supplementary Table 1A). The ratio of non-target and target trials was set at 70% (35 trials) to 30% (15 trials) per Block oriented on previous studies that have addressed the validity of the computerized *n*-back task (Miller et al., 2009; Jaeggi et al., 2010). Further details of the general and soccer-specific task are presented in Table 1.

Control variables

Motivation of the participants was assessed as a control variable. Accordingly, they answered the question "How motivated are you at this moment?" on a visual analog scale (VAS; Crichton, 2001) with two endpoints from 0 (not at all) to 100 (highly) before performing the computerized and SoccerBot100 tasks. VAS are commonly used to assess moods, stress, or emotions. Within the scope of such investigations, the reliability and validity of the VAS have also been confirmed (e.g., Pfennings et al., 1995). In addition, perceived physical exertion (RPE) of the participants was assessed using the 15-point Borg scale for ratings of perceived exertion (Borg, 1970). The RPE scale is a frequently used measurement that is considered valid based on determined high correlations of the ratings and different physiological variables such as heart rate (Borg, 1982).

Finally, we assessed perceived fun and perceived stress regarding the tasks after players performed them. Players were asked to answer the questions "How much fun did you have doing the current task?" and "How stressful did you find the task?" on a VAS scale from 0 (none) to 100 (a lot) following the respective task. All scales were presented in digital form on a tablet.

Procedure

For the final experiment, players were recruited through inquiries with regional amateur teams and announcements at the university. The experiment was conducted in the laboratory of the Department of Movement Neuroscience at Leipzig University and lasted approximately 30 min for each player. The study followed a cross-sectional approach with a within-subject design.

First, participants were asked to fill out demographic and soccer-specific questionnaires. This was followed by the general 3-back task on the computer. After that, participants were asked to warm up individually for 5–10 min to reduce the risk of injuries, before starting the sport-specific 3-back task in the SoccerBot100. The assessment of

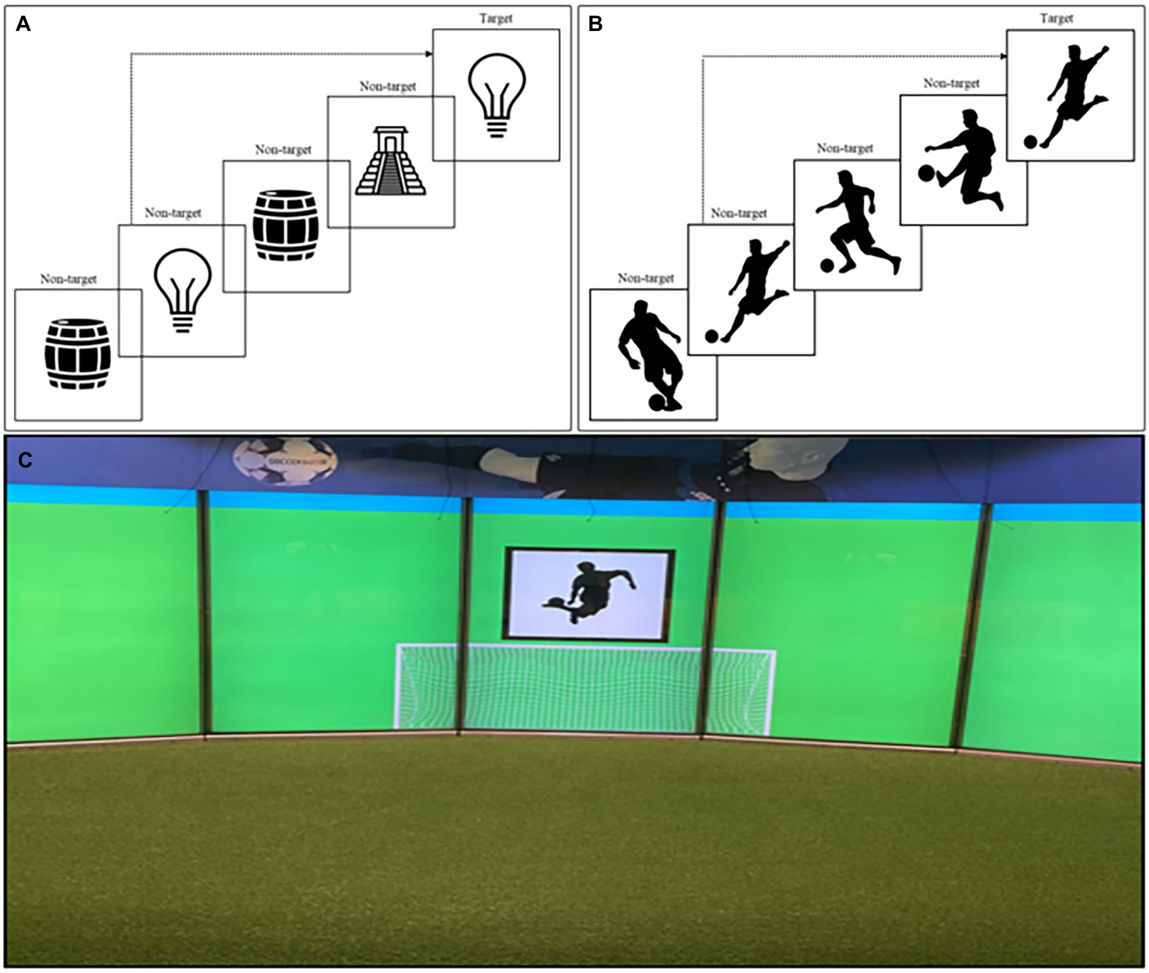


FIGURE 1
Applied stimuli in the computerized 3-back task **(A)**, adapted for the SoccerBot100 **(B)** and the provided soccer-specific setting **(C)**. Images of SoccerBot reproduced with permission from Umbrella Software.

player's motivation and perceived exertion was conducted before participants performed the tasks to control for potential differences in motivation and physical load during the experiment as well as possible preload due to training or work before testing that could have influenced test performance. At this point, it is important to note that the order of the versions (i.e., first computer task and second soccer-specific task) was fixed in order to familiarize the players with each task and reduce the number of practice trials, and therefore the physical load, in the SoccerBot100 (see Musculus et al., 2022).

Data preparation

For the computerized and for the soccer-specific 3-back task, a filter was used to identify all missed target trials (PC: 35.79%; soccer-specific: 33.80%). In addition, all responses to non-target trials (i.e., false alarms) were determined (PC: 9.82%, soccer-specific: 5.71%) followed by the exclusion of the corresponding response times. Thus, the mean response time is calculated only based on target trials that the participants correctly identified and responded to. In a second filter, for the computerized task, all trials with response times lower than 200 ms or higher than 3,000 ms (0.0%) were excluded (e.g., Lautenbach et al., 2016). For the soccer-specific task, the same filter (0.0%) was used but with 400 ms as the lower bound due to longer responses times for the whole-body movement (Morya et al., 2003). In addition, a third filter excluded all response times that deviated ±3 *SD* from the individual mean were excluded (computerized 0.0%, soccer-specific 0.0%). Both filters were applied to control for extreme results caused by, for example, speculating or waiting too long, thus being inattentive to the task.

In order to calculate the overall accuracy in a first step, the percentage of correct answers to target trials and the percentage of false alarms were determined. Then, the percentage of correct target trials (e.g., 70%) minus the percentage of incorrect answers for non-targets (i.e., false alarms, 10%) was calculated (e.g., 60% overall accuracy). Additionally, we investigated the percentage of missed target trials (e.g., 30%) as this provides a measurement of how many correct answers went into the analysis of response time, which is only measured based on correct responses to target trials. This additional measure is relevant as some athletes might be fast in their response time but only a small number of trials were answered correctly.

Overall, three players had to be excluded because of incomplete data sets (two in the computerized task because only half of all trials were recorded, one in the soccer-specific task because incomplete data collection). Thus, the analyses included a total of 57 participants.

TABLE 1 Comparison of general computer *n*-back task and soccer-specific *n*-back task.

Variable	*n*-back task for working memory	
	Computerized	Soccer-specific
No. practice trials	One block with 10 trials	Two blocks with 17 trials
	(Two targets, eight non-target)	(Five targets, 12 non-target)
Feedback practice trials	No	Yes (after played pass)
No. test trials	100 (30 targets, 70 non-targets)	100 (30 targets, 70 non-targets)
No. test blocks (trials per block)	2 (50)	2 (50)
Break between blocks	30 s	30 s
Response correspondence	Fingertip on keyboard (button "A" for targets; no button press for non-targets)	Pass to goal under stimuli for targets: no pass for non-targets
Stimulus presentation	10 different images of various, non-specific objects (e.g., lamp, chair, or bicycle)	10 different images (silhouettes) of soccer-specific actions (e.g., duel, shot, and dribble)
Randomization of presented stimuli	Yes	No
Fixator (fixation duration)	Black screen without Fixator (2,500 ms)	Black + (1,500 ms)
Response–stimulus interval	Trial presented for the shape of 500 ms, another 2,500 ms before presenting the next shape	Trial presented for 2,500 ms, Inter-Stimulus-Interval (1,500 ms)
Response time out	3,000 ms	4,000 ms
Cronbach's alpha (reaction time)	0.72	0.78
Split-Half Reliability (reaction time)	0.72	0.78

Data analyses

The dependent variables were first checked for normality and outliers. For both tasks, accuracy and response time parameters were normally distributed. Two outliers were detected for the 3-back task with regard to accuracy values in the general computerized task. For the soccer-specific task in the SoccerBot100, no outliers were detected. All data were analyzed using SPSS Statistics, version 25. Initially, the level of significance was set at $p < 0.05$ for all analyses.

First, to control for potential influences of motivation and perceived exhaustion, we checked whether there was a difference in motivation or perceived exhaustion prior to the computerized and soccer-specific task by running two paired *t*-tests. If differences were found, we followed up by calculating Pearson correlations with the dependent variables of accuracy and response time.

To test convergent validity for the soccer-specific task (Hypothesis 1), we calculated Pearson correlations between response time and accuracy for the general, computerized task, and the adapted soccer-specific version. In addition, we controlled for potential learning effects by calculating paired *t*-tests for response times and accuracy between block 1 and block 2 within the respective tasks. Finally, we ran dependent *t*-test to assess the fun and stress participants perceived during the two versions of the tasks.

Results

Statistical analyses indicated the same pattern of results when outliers were included and thus, all analyses are reported including the outliers. The descriptive statistics for response times and accuracy for the computerized general and soccer-specific versions of the 3-back task are shown in Table 2. Reliability, assessed *via* split-half reliability (coefficient *r*) and Cronbach's Alpha for response time parameters, show high values for both computerized general ($r = 0.72$; $\alpha = 0.72$) and soccer-specific task ($r = 0.78$; $\alpha = 0.78$).

Convergent validity

For the computerized and the soccer-specific working memory tasks, correlational analyses revealed significant positive correlations for response time ($r = 0.446$, $p < 0.001$) and overall accuracy ($r = 0.401$, $p < 0.001$). The analyses regarding the missed targets confirm the correlations ($r = 0.352$, $p < 0.001$) as well as the false alarms ($r = 0.409$, $p < 0.001$). Further results of correlational analyses are presented in Table 3.

Control variables (motivation, perceived exhaustion, stress, and perceived fun)

Players reported to be significantly higher motivated prior to the computerized general ($M = 77.93$, $SD = 16.24$) in comparison to the soccer-specific task ($M = 68.28$, $SD = 21.78$), $t(56) = 4.13$, $p < 0.001$, $d = 0.548$. A Pearson correlation revealed significant positive correlations between motivation before the soccer-specific task and response times in the soccer-specific task ($r = 0.288$, $p = 0.030$).

The perceived exhaustion was significantly lower prior to the general computerized task ($M = 20.51$, $SD = 19.13$) in comparison to the soccer-specific task ($M = 34.77$, $SD = 24.26$), $t(56) = 4.9$, $p < 0.001$, $d = 0.654$. A Pearson correlation revealed significant negative correlations between response times and perceived exhaustion ($r = -0.289$, $p = 0.030$) in the

SoccerBot100. No significant differences in perceived stress were shown after the computerized ($M=60.14$; $SD=24.20$) and the soccer-specific task ($M=54.35$, $SD=25.58$), $t(56)=1.79$, $p=0.078$, $d=0.237$.

Finally, participants perceived the task in the SoccerBot100 to be significantly more fun ($M=73.56$, $SD=22.09$) than the computerized task ($M=44.47$, $SD=25.22$), $t(56)=8.86$, $p<0.001$, $d=0.436$. A Pearson correlation, however, did not show any significant correlations between perceived fun and performance in the computerized or soccer-specific task.

Learning effects

For the computerized task, no significant differences in response time was found between the first ($M=992.70$, $SD=267.29$) and the second block ($M=950.34$, $SD=247.59$), $t(56)=1.32$, $p=0.190$, $d=0.185$. This also applies to the mean accuracy values in the first ($M=49.84\%$, $SD=19.13\%$) and second block ($M=53.03\%$, $SD=19.39\%$), $t(56)=1.01$, $p=0.314$, $d=0.134$.

TABLE 2 Descriptive statistics for the general, computerized, and soccer-specific versions of the tasks measuring working memory ($n=57$).

Task	Descriptive statistics			
	M	*SD*	Min	Max
Computerized				
RT, target trials (ms)	970.2	231.61	601.6	1,505
Overall accuracy, all trials (%)	51.44	15.02	10.91	88.48
False alarms (%)	9.82	5.2	2.86	32.86
Missed targets (%)	35.78	13.47	0	70
Soccer-specific				
RT, target trials (ms)	1542.95	192.9	1117.06	1871.73
Overall accuracy, all trials (%)	60.18	15.02	20.95	90
False alarms (%)	5.66	3.74	0	15.71
Missed targets (%)	33.8	13.76	6.67	63.33

RT, response time.

Similar results were shown in the soccer-specific task. For response times, no differences were found between the first ($M=1527.33$, $SD=216.08$) and second half ($M=1555.57$, $SD=209.65$) of the test runs, $t(56)=1.18$, $p=0.240$, $d=0.156$. Also, no differences were found for accuracy ($M_{1st\ block}=59.04\%$, $SD_{1st\ block}=17.91\%$; $M_{2nd\ block}=61.32\%$, $SD_{2nd\ block}=15.39\%$), $t(56)=1.01$, $p=0.371$, $d=0.134$.

Discussion

Following the previous development of tasks to assess inhibition and cognitive flexibility with soccer-specific stimuli and soccer-specific motor response (i.e., pass), the aim of this study was to develop and validate a task measuring working memory (updating) in the same setting. For convergent validity of the general and the soccer-specific task, we found significant positive correlations for response time as well as accuracy parameters of both tasks. These results as well as the also acceptable values of the reliability indicate that the adapted 3-back task is applicable to measure working memory in adult soccer players.

In general, the use of the *n*-back task to determine individual differences in working memory has been controversially discussed (Jaeggi et al., 2010). Due to weak correlations with performance in other working memory tasks, this discussion mainly focused on the question of whether the *n*-back task only measures working memory (Kane et al., 2007; Miller et al., 2009). Given the dynamic nature of the task (Frost et al., 2021) and complexity of EFs (Miyake et al., 2000), researchers also highlight the potential impact of additional processes. For example, Miller et al. (2009, p. 716) concluded, that "*n*-back accuracy may rely more on information processing speed or motor speed than on working memory…," independent of the applied *n*-back load that was investigated (1-, 2-, and 3-back loads).

Against the background of a complex performance structure, it can be assumed that working memory performance in soccer is also subject to these processes. Players must not only be able to retrieve and update information, but also adapt their (motor) actions. It is possible that these demands are also represented by the *n*-back task, since studies with elite soccer players show correlations with soccer performance. It was shown that scores from the *n*-back task correlated with goals scored during the season as well as a superiority of elite athletes over athletes and non-athletes (Vestberg et al., 2017; Holfelder et al., 2020).

With respect to the significant but moderate correlations detected for response time and response accuracy for the assessment of convergent validity, the differences between the tasks must be considered. Although the soccer-specific task was based on the computer-based task and is supposed to measure the same construct, there are methodological differences that might limit higher correlations between the tasks. With the implementation in a different

TABLE 3 Correlations for response time and accuracy values between computerized and soccer-specific 3-back task.

Computerized task	Variable	Soccer-specific task			
		RT_target trials	Acc_all trials	Acc_false alarms	Acc_missed targets
	RT_target trials	0.446**	−0.079	0.00	0.102
	Acc_all trials	−0.180	0.401**	−0.242	−0.366**
	Acc_false alarms	0.072	−0.079	0.409**	−0.018
	Acc_missed targets	0.176	−0.357**	0.109	0.352**

RT, response time; Acc, Accuracy. *$p<0.05$; **$p<0.001$.

environment as well as the differences in terms of response modality and presented stimuli, relevant parameters such as the duration of the stimuli and the time for response were also adjusted. It is possible that these aspects provoke different response behavior. In this context, common method variance (Bryman, 1989) could also be present. This describes variance caused by the measurement method itself rather than the constructs that the measurements represent. Additionally, response format and the general context of the applied methods (Podsakoff, 2003) differ between the computerized and soccer-specific task, despite the fundamentally same construct that the tasks measure (i.e., working memory).

Under closer examination of the results of both tasks, it is noticeable that the accuracy in the soccer-specific task is considerably higher. This may be due to habituation or learning effects between tasks, as the task in the SoccerBot was always performed second. However, at least within the tasks, there were no indications of learning effects. Another explanation would be the longer presentation of the stimuli in the soccer-specific task due to the more complex motor responses. This is consistent with studies showing that image recognition, as well as numerical discrimination accuracy, increases with longer stimulus duration (Bird and Cook, 1979). In this context, it has been shown that information reception as well as memorizing of stimuli is facilitated by longer presentation through repeated recall (Inglis and Gilmore, 2013; Pergher et al., 2020). With respect to the current soccer-specific task, it might also be plausible to assume that better accuracy might be due to the more relatable stimuli (i.e., soccer-specific pictures) used. This assumption aligns with previous studies that emphasized the importance of the strength of the stimulus in making fast and accurate decisions (Palmer et al., 2005). Hence, familiar stimuli are easier to process and effectiveness is even further increased for meaningful stimuli (Lupyan and Spivey, 2008). With regard to the sample of experienced soccer players, the soccer-specific images may have been of different meaning and thus, more relatable than the neutral objects in the computerized version. With regard to the different images in the tasks, the similarity of the images could also play a role here. The more similar the stimuli used, the more likely they are to be confused by the participants, thus, producing false alarms. However, more false alarms were produced in the computer task than in the soccer-specific task, although the images presented should be more clearly distinguishable than the images of soccer actions (for overview of all images used, see Supplementary material section C). Thus, it seems more likely that the shorter presentation of the stimuli and reaction time in the computer task provokes false alarms.

With regard to the considered influence of control variables, ambiguous results were shown. Motivation was significantly higher prior to the computer task than prior to the soccer-specific task whereas perceived exhaustion was higher prior to the soccer-specific task. Both results can be explained by the previously performed computer task itself. In other words, motivation decreased after the computer task and perceived exhaustion (mainly cognitive exhaustion also referred to as cognitive or mental fatigue; Sievertsen et al., 2016; Smith et al., 2018) increases which has been shown in previous research focusing on such laboratory tasks (O'Keeffe et al., 2020). There was moreover a negative correlation between exhaustion and response times in the soccer-specific task. Since the perceived exertion was assessed before the soccer-specific task and was significantly lower than before the task on the computer, it can be assumed that this is mainly cognitive exertion. Accordingly, the results are in line with studies on mental fatigue and its associated decline of soccer-specific performance factors including decision-making skills (Smith et al., 2016). Interestingly however, accuracy was higher in the soccer-specific task and thus, we would argue that this did not affect cognitive performance in the soccer-specific task.

Further, we found a positive correlation between motivation and response time in the soccer-specific task, indicating that higher motivation is related to slower response times in the soccer-specific task. However, as we did not measure motivation and perceived exhaustion after the soccer-specific task, and results actually indicated that players had more fun performing the soccer-specific task (see also Musculus et al., 2022), we would argue that the differences in prior motivation and perceived exhaustion to the tasks are negligible. Though, with regard to motivation and experienced fun, which correlated negatively to response time in the soccer-specific task, our results seem to contrast with findings showing that enjoyment leads to faster motor actions (see, e.g., Rathschlag and Memmert, 2013). However, results are hardly comparable as athletes had to react as fast as possible to presented stimuli in our study, thus they experience a cognitive load, whereas in Rathschlag and Memmert (2013), they had to throw a ball as fast as possible without responding to a stimulus.

Since this study primarily aimed at testing the validity of the developed soccer-specific *n*-back task, further investigations with regard to interindividual differences that could be reflected by performance of the task are relevant (see, e.g., Kalén et al., 2021). In this context, future research should investigate soccer players with different expertise levels and age groups as this might help clarify which cognitive functions are either developing (De Luca et al., 2003) or determined by expertise (Verburgh et al., 2014).

Limitations

This study has some methodological limitations. The first is related to the study design: For each participant, the soccer-specific task was conducted after the computerized task. This could have potentially resulted in learning effects, which, on the one hand, were intended to reduce physical exhaustion and prevent injuries in the SoccerBot but, on the other hand, might have biased the results in the SoccerBot. However, potential learning effects within the two blocks of the respective tasks have not been identified. A further methodological limitation of the SoccerBot is the starting point for passing and response time assessment. The starting point from which the passes are played is located in the center of the artificial grass area, 5 m away from the screens. We have placed a marker and instructed the players to play from this spot, nevertheless, slight variations in movement execution are possible. Response times were inferred from a camera that assesses 120 frames/s (see also Musculus et al., 2022). Based on our results, however, the response time measures seem to be sufficient to detect variance in the response times similar to the computerized task. With regard to ecological validity of the developed task, we are aware that the representativeness of the applied stimuli is somewhat limited. The transfer of the required perception-action coupling for on-field performance is restricted as the players in the pictures often perform actions with a ball. In order to increase the representativeness of actual game situations, it would be conceivable to depict players in free spaces demanding the ball. The challenge here, however, is that differences between the images would only be marginal and could thus, easily lead to other methodological limitations such as an increase in false alarms. If the players in the pictures only differed in size and shape, it would be very difficult for the participants to distinguish and recall these differences in the short time span.

Conclusion

In the present project, we aimed to develop a soccer-specific working memory task (*n*-back) in the SoccerBot100 and thereby expanding the repertoire of measuring soccer-specific inhibition and cognitive flexibility. Given significant correlations for response time and accuracy between the general, computerized and the adapted soccer-specific 3-back tasks, indicating convergent validity, we would argue that the task is applicable to measure soccer-specific working memory. Accordingly, together with the previously validated task, it is now possible to assess all three core EFs in a soccer-specific manner. Thereby, further investigations on the tasks' external validation, for example in the context of other soccer-specific motor skills or the overall game performance are possible (see also Scharfen and Memmert, 2019; Heilmann et al., 2022). Finally, these further studies may allow conclusions to be drawn about the importance of EFs and enable to examine the expression of the individual EFs and their interaction.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Ethics Advisory Board, Leipzig University. The patients/participants provided their written informed consent to participate in this study.

Author contributions

SK, FL, LM, MR, and PW: idea. SK and FL: conceptualization. SK: planning of the study, literature research, data analysis, and first draft. SK and RS: data collection and data preparation. FL: revision and supervision. All authors contributed to the article and approved the submitted version.

Funding

SK receives a promotional grant (LAU-R-G-31-1-1020) as part of the Saxony state graduate scholarship program (Landesgraduiertenstipendium) under the supervision of FL and A-ME. Publishing was funded by the Open Access Publishing Fund of Leipzig supported by the German Research Foundation within the program Open Access Publication Funding.

Acknowledgments

We thank all the players who participated in our study. We also thank the Department of Movement Neuroscience from Leipzig University, especially Patrick Ragert and Daniel Carius for providing access to the SoccerBot100. Furthermore, we would like to thank Umbrella Software GmbH, especially Sven Schlüchtermann, for the cooperation and the implementation of the task. We would also like to acknowledge the work of Lisa Musculus, Martin Leo Reinhard and Peter Weigel who contributed to our first project, which formed the basis for the current project. In addition, we would like to thank Andy Borchert and Robin Schrader from RB Leipzig for the collaborative exchange on the development of the study, as well as Robin Schrader for his support in data collection. Also, we thank the Saxony state graduate scholarship program for providing funding for Simon Knöbel. Finally, we acknowledge funding by the Open Access Publishing Fund of Leipzig supported by the German Research Foundation within the program Open Access Publication Funding.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.1026017/full#supplementary-material

References

Beavan, A. (2019). Extraordinary tools require extraordinary evidence. *Sci. Med. Football* 3, 263–264. doi: 10.1080/24733938.2019.1678948

Beavan, A., Spielmann, J., Mayer, J., Skorski, S., Meyer, T., and Fransen, J. (2020). The rise and fall of executive functions in high-level football players. *Psychol. Sport Exerc.* 49:101677. doi: 10.1016/j.psychsport.2020.101677

Bird, J. E., and Cook, M. (1979). Effects of stimulus duration and ISI on accuracy and transference errors in pictorial recognition. *Mem. Cogn.* 7, 469–475. doi: 10.3758/BF03198263

Borg, G. (1970). Perceived exertion as an indicator of somatic stress. *Scand. J. Rehabil. Med.* 2, 92–98.

Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Med. Sci. Sports Exerc.* 14, 377–381. doi: 10.1249/00005768-198205000-00012

Bryman, A. (1989). *Research Methods and Organization Studies*. New York: Routledge

Carling, C. (2010). Analysis of physical activity profiles when running with the ball in a professional soccer team. *J. Sports Sci.* 28, 319–326. doi: 10.1080/02640410903473851

Conway, A. R., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., and Engle, R. W. (2005). Working memory span tasks: a methodological review and user's guide. *Psychon. Bull. Rev.* 12, 769–786. doi: 10.3758/BF03196772

Crichton, N. (2001). Visual analogue scale (VAS). *J. Clin. Nurs.* 10:706.

De Luca, C. R., Wood, S. J., Anderson, V., Buchanan, J. A., Proffitt, T. M., Mahony, K., et al. (2003). Normative data from the Cantab. I: development of executive function over the lifespan. *J. Clin. Exp. Neuropsychol.* 25, 242–254. doi: 10.1076/jcen.25.2.242.13639

Diamond, A. (2013). Executive functions. *Annu. Rev. Psychol.* 64, 135–168. doi: 10.1146/annurev-psych-113011-143750

Ericsson, K. A. (2003). How the expert performance approach differs from traditional approaches to expertise in sport: in search of a shared theoretical framework for studying expert performance in *Expert Performance in Sports: Advances in Research on Sport Expertise*. eds. J. L. Starkes and K. A. Ericsson (Champaign, Illinios, United states: Human Kinetics, 371–402

Farrow, D., and Abernethy, B. (2003). Do expertise and the degree of perception—action coupling affect natural anticipatory performance? *Perception* 32, 1127–1139. doi: 10.1068/p3323

Frost, A., Moussaoui, S., Kaur, J., Aziz, S., Fukuda, K., and Niemeier, M. (2021). Is the n-back task a measure of unstructured working memory capacity? Towards understanding its connection to other working memory tasks. *Acta Psychol.* 219:103398. doi: 10.1016/j.actpsy.2021.103398

Heilmann, F., Weigel, P., and Wollny, R. (2021). Analysis of cognitive abilities measured in a laboratory—controlled 360 ° simulation in soccer. *German J. Exerc. Sport Res.* 51, 302–311. doi: 10.1007/s12662-021-00713-x

Heilmann, F., Wollny, R., and Lautenbach, F. (2022). Inhibition and calendar age explain variance in game performance of youth soccer athletes. *Int. J. Environ. Res. Public Health* 19. doi: 10.3390/ijerph19031138

Hockey, A., and Geffen, G. (2004). The concurrent validity and test–retest reliability of a visuospatial working memory task. *Intelligence* 32, 591–605. doi: 10.1016/j.intell.2004.07.009

Holfelder, B., Klotzbier, T. J., Eisele, M., and Schott, N. (2020). Hot and cool executive function in elite-and amateur-adolescent athletes from open and closed skills sports. *Front. Psychol.* 11:694. doi: 10.3389/fpsyg.2020.00694

Huijgen, B. C. H., Leemhuis, S., Kok, N. M., Verburgh, L., Oosterlaan, J., Elferink-Gemser, M. T., et al. (2015). Cognitive functions in elite and sub-elite youth soccer players aged 13 to 17 years. *PLoS One* 10, 1–13. doi: 10.1371/journal.pone.0144580

Inglis, M., and Gilmore, C. (2013). Sampling from the mental number line: how are approximate number system representations formed? *Cognition* 129, 63–69. doi: 10.1016/j.cognition.2013.06.003

Jaeggi, S. M., Buschkuehl, M., Perrig, W. J., and Meier, B. (2010). The concurrent validity of the N-back task as a working memory measure. *Memory* 18, 394–412. doi: 10.1080/09658211003702171

Kalén, A., Bisagno, E., Musculus, L., Raab, M., and Pérez-ferreiro, A. (2021). The role of domain-specific and domain-general cognitive functions and skills in sports performance: a meta-analysis. *Psychol. Bull.* 147, 1290–1308. doi: 10.1037/bul0000355

Kane, M. J., Conway, A. R., Miura, T. K., and Colflesh, G. J. (2007). Working memory, attention control, and the N-back task: a question of construct validity. *J. Exp. Psychol. Learn. Mem. Cogn.* 33, 615–622. doi: 10.1037/0278-7393.33.3.615

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. *J. Exp. Psychol.* 55, 352–358. doi: 10.1037/h0043688

Kittelberger, T. (2018). "Die Entwicklung kognitiver Fähigkeiten von Spielern am Beispiel der Helix" in *People Analytics im Profifußball*. eds. R. Lanwehr and J. Mayer (Wiesbaden: Springer Gabler), 171–203.

Lautenbach, F., Musculus, L., Knöbel, S., Reinhard, M. L., Holst, T., Poimann, D., et al. (2022). Beiträge aus der Angewandten Sportpsychologie. *Z. Sportpsychol.* 29, 19–29. doi: 10.1026/1612-5010/a000351

Lautenbach, F., Putman, P., Angelidis, A., Laborde, S. J. P., and Raab, M. (2016). Attentional distraction by negative sports words in athletes under low- and high-pressure conditions: evidence from the sport emotional stroop task. *Sport Exerc. Perform. Psychol.* 5, 296–307. doi: 10.1037/spy0000073

Lumsden, J., Edwards, E. A., Lawrence, N. S., Coyle, D., and Munafò, M. R. (2016). Gamification of cognitive assessment and cognitive training: a systematic review of applications and efficacy. *JMIR Serious Games* 4:e5888. doi: 10.2196/games.5888

Lupyan, G., and Spivey, M. J. (2008). Perceptual processing is facilitated by ascribing meaning to novel stimuli. *Curr. Biol.* 18, R410–R412. doi: 10.1016/j.cub.2008.02.073

Memmert, D. (2019). *Fußballspiele werden im Kopf entschieden: Kognitives Training, Kreativität und Spielintelligenz im Amateur- und Leistungsbereich*. Aachen: Meyer & Meyer.

Miller, K. M., Price, C. C., Okun, M. S., Montijo, H., and Bowers, D. (2009). Is the n-back task a valid neuropsychological measure for assessing working memory? *Arch. Clin. Neuropsychol.* 24, 711–717. doi: 10.1093/arclin/acp063

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., and Wager, T. D. (2000). The Unity and Diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cogn. Psychol.* 41, 49–100. doi: 10.1006/cogp.1999.0734

Morya, E., Ranvaud, R., and Pinheiro, W. M. (2003). Dynamics of visual feedback in a laboratory simulation of a penalty kick. *J. Sports Sci.* 21, 87–95. doi: 10.1080/0264041031000070840

Murr, D., Feichtinger, P., Larkin, P., O'Connor, D., and Höner, O. (2018). Psychological talent predictors in youth soccer: a systematic review of the prognostic relevance of psychomotor, perceptual-cognitive and personality-related factors. *PLoS One* 13, 1–24. doi: 10.1371/journal.pone.0205337

Musculus, L., Lautenbach, F., Knöbel, S., Reinhard, M. L., Weigel, P., Gatzmaga, N., et al. (2022). An assist for cognitive diagnostics in soccer: two valid tasks measuring inhibition and cognitive flexibility in a soccer-specific setting with a soccer-specific motor response. *Front. Psychol.* 13:867849. doi: 10.3389/fpsyg.2022.867849

Nougier, V., Stein, J. F., and Bonnel, A. M. (1991). Information-processing in sport and orienting of attention. *Int. J. Sport Psychol.* 22, 307–327.

O'Keeffe, K., Hodder, S., and Lloyd, A. (2020). A comparison of methods used for inducing mental fatigue in performance research: individualised, dual-task and short duration cognitive tests are most effective. *Ergonomics* 63, 1–12. doi: 10.1080/00140139.2019.1687940

Palmer, J., Huk, A. C., and Shadlen, M. N. (2005). The effect of stimulus strength on the speed and accuracy of a perceptual decision. *J. Vis.* 5:1. doi: 10.1167/5.5.1

Pergher, V., Shalchy, M. A., Pahor, A., Van Hulle, M. M., Jaeggi, S. M., and Seitz, A. R. (2020). Divergent research methods limit understanding of working memory training. *J. Cogn. Enhanc.* 4, 100–120. doi: 10.1007/s41465-019-00134-7

Pfennings, L., Cohen, L., and van der Ploeg, H. (1995). Preconditions for sensitivity in measuring change: visual analogue scales compared to rating scales in a Likert format. *Psychol. Rep.* 77, 475–480. doi: 10.2466/pr0.1995.77.2.475

Podsakoff, N. P. (2003). Common method biases in behavioral research: a critical review of the literature and recommended remedies. *J. Appl. Psychol.* 88, 879–903. doi: 10.1037/0021-9010.88.5.879

Rathschlag, M., and Memmert, D. (2013). The influence of self-generated emotions on physical performance: an investigation of happiness, anger, anxiety, and sadness. *J. Sport Exerc. Psychol.* 35, 197–210. doi: 10.1123/jsep.35.2.197

Saal, C., Krug, J., Zinner, J., and Mayer, J. (2015). Footbonaut. Ein innovatives mess- und Informationssystem im Fusball.[Footbonaut. An innovative measurement and information system in football]. *Leistungssport* 45, 13–15.

Scharfen, H. E., and Memmert, D. (2019). The relationship between cognitive functions and sport-specific motor skills in elite youth soccer players. *Front. Psychol.* 10:817. doi: 10.3389/fpsyg.2019.00817

Scharfen, H. E., and Memmert, D. (2021). Fundamental relationships of executive functions and physiological abilities with game intelligence, game time and injuries in elite soccer players. *Appl. Cogn. Psychol.* 35, 1535–1546. doi: 10.1002/acp.3886

Sievertsen, H. H., Gino, F., and Piovesan, M. (2016). Cognitive fatigue influences students' performance on standardized tests. *Proc. Natl. Acad. Sci.* 113, 2621–2624. doi: 10.1073/pnas.1516947113

Smith, M. R., Coutts, A. J., Merlini, M., Deprez, D., Lenoir, M., and Marcora, S. M. (2016). Mental fatigue impairs soccer-specific physical and technical performance. *Med. Sci. Sports Exerc.* 48, 267–276. doi: 10.1249/MSS.0000000000000762

Smith, M. R., Thompson, C., Marcora, S. M., Skorski, S., Meyer, T., and Coutts, A. J. (2018). Mental fatigue and soccer: current knowledge and future directions. *Sports Med.* 48, 1525–1532. doi: 10.1007/s40279-018-0908-2

Söhnlein, K., and Borgmann, S. (2018). "Diagnostik von Exekutivfunktionen im Fußball" in *People Analytics im Profifußball*. eds. R. Lanwehr and J. Mayer (Berlin, Heidelberg, New York: Springer)

Van Maarseveen, M. J. J., Oudejans, R. R. D., Mann, D. L., and Savelsbergh, G. J. P. (2018). Perceptual-cognitive skill and the in situ performance of soccer players. *Q. J. Exp. Psychol.* 71, 455–470. doi: 10.1080/17470218.2016.1255236

Verburgh, L., Scherder, E. J. A., Van Lange, P. A. M., and Oosterlaan, J. (2014). Executive functioning in highly talented soccer players. *PLoS One* 9, 1–7. doi: 10.1371/journal.pone.0091254

Vestberg, T., Gustafson, R., Maurex, L., Ingvar, M., and Petrovic, P. (2012). Executive functions predict the success of top-soccer players. *PLoS One* 7:e34731. doi: 10.1371/journal.pone.0034731

Vestberg, T., Jafari, R., Almeida, R., Maurex, L., Ingvar, M., and Petrovic, P. (2020). Level of play and coach-rated game intelligence are related to performance on design fluency in elite soccer players. *Sci. Rep.* 10, 1–10. doi: 10.1038/s41598-020-66180-w

Vestberg, T., Reinebo, G., Maurex, L., Ingvar, M., and Petrovic, P. (2017). Core executive functions are associated with success in young elite soccer players. *PLoS One* 12:e0170845. doi: 10.1371/journal.pone.0170845

Voss, M. W., Kramer, A. F., Basak, C., Prakash, R. S., and Roberts, B. (2010). Are expert athletes "expert" in the cognitive laboratory? A meta-analytic review of cognition and sport expertise. *Appl. Cogn. Psychol.* 24, 812–826. doi: 10.1002/acp.1588

Wallace, J. L., and Norton, K. I. (2014). Evolution of world cup soccer final games 1966-2010: game structure, speed and play patterns. *J. Sci. Med. Sport* 17, 223–228. doi: 10.1016/j.jsams.2013.03.016

Walton, C. C., Keegan, R. J., Martin, M., and Hallock, H. (2018). The potential role for cognitive training in sport: more research needed. *Front. Psychol.* 9:1121. doi: 10.3389/fpsyg.2018.01121

frontiers | Frontiers in Psychology

TYPE Conceptual Analysis
PUBLISHED 27 October 2023
DOI 10.3389/fpsyg.2023.1252201

OPEN ACCESS

EDITED BY
Karen Zentgraf,
Goethe University Frankfurt, Germany

REVIEWED BY
Stefan Künzell,
University of Augsburg, Germany
Gualtiero Piccinini,
University of Missouri–St. Louis, United States

*CORRESPONDENCE
Sigmund Loland
sigmundl@nih.no

RECEIVED 03 July 2023
ACCEPTED 12 October 2023
PUBLISHED 27 October 2023

CITATION
Loland S, Ettema G and Sandbakk Ø (2023) The study of movement skills in sports: toward an integrative approach.
Front. Psychol. 14:1252201.
doi: 10.3389/fpsyg.2023.1252201

The study of movement skills in sports: toward an integrative approach

Sigmund Loland[1]*, Gertjan Ettema[2] and Øyvind Sandbakk[2]

[1]Norwegian School of Sport Sciences, Oslo, Norway, [2]Norwegian University of Science and Technology, Trondheim, Norway

The article commences with a fundamental objective: to comprehend movement skills in sports in a manner that can bridge the dualist gap between experiential qualities observed in practice and theoretical and mechanistic explanations. Drawing inspiration from Kuhn's concept of scientific paradigms, practical examples from skiing research, and innovative insights into the integration of phenomenology and mechanistic explanation in cognitive science, we have outlined a three-step integrative approach. The first step entails the development of phenomenological descriptions of the primary experiential qualities inherent in the execution of the skills being investigated. In the second step, phenomenological descriptions play a pivotal role by setting constraints and delineating a space for the elaboration of multilevel mechanistic analyses. These analyses draw upon insights from various fields, encompassing biomechanics, motor control approaches, expertise studies, and cognitive science. The third step involves the systematization of findings and the formulation of sport-specific movement skills theories. We contend that such theories hold substantial significance as they serve as valuable supplements to skill studies conducted within rigid, nomological frameworks. Sport-specific theories include descriptions of first-person experiential qualities and can contribute to bridging the theory-practice gap effectively.

KEYWORDS

movement skills, mechanistic explanations, phenomenology, integrative approach, sports

Introduction

Human movement skills, understood as functional and efficient solutions to movement tasks, can be studied in several ways. One main approach is based on natural science in which the body and its movements are described in objective, quantitative terms and explained mechanistically with the help of scientific disciplines such as biomechanics and motor control and learning. For example, a traditional motor control approach starts from insights into the neuromuscular interplay between a hierarchy of central nervous system (CNS) structures and sensory inputs from the involved structures (e.g., muscles). Skill development is explained by the plasticity and adaptability of the human organism.

A second approach emphasizes the subjective first-person perspective and analyses experiential qualities in movement. With inspiration from phenomenology, descriptions of movement skill execution are presented with concepts such as rhythm and flow and with references to specific experiential qualities as found in the 'tribal' language of athletes and coaches. The approach can connect to constructivist approaches in the social sciences, where learned movement patterns are seen as outcomes of socialization within the context of cultural norms and values.

There are major differences between these approaches. They are based on different epistemological and methodological premises. The mechanistic approach offers explanations and predictions within well-defined theoretical frameworks. The phenomenological approach represents the quest to describe and understand practice as 'lived' and experienced by practitioners.

The question to be addressed here is whether the mechanistic and phenomenological approaches are mutually exclusive or whether the apparent gaps can be overcome in scientifically sound ways. Firstly, and with the help of Kuhn's idea of scientific paradigms, we will discuss the challenge of paradigmatic incommensurability, questioning to what extent and in what sense such a challenge may exist between phenomenological and mechanistic accounts. Secondly, and with examples from existing sports research, we will examine limitations and possibilities in the handing this challenge. With backing in works by Montero (2016) and Pokropski (2021) in particular, we will point to solutions in which phenomenology and mechanistic approaches can be integrated. Thirdly, and on this basis, we will outline the main steps of an integrative approach to movement skills.

Kuhn, paradigms, and incommensurability

Kuhn's (1962/1996) work on the structure of scientific revolutions, particularly his conceptualization of scientific paradigms, has exerted a significant impact on the understanding of scientific development. Although receiving criticism for his theory of paradigm change (Mizrahi, 2018), the scientific paradigm concept has proven fertile and has become a standard reference in academic discourse. In the most extensive interpretation, a scientific paradigm consists of a disciplinary matrix, that is, a basic pattern of metaphysical assumptions, theoretical and methodological concepts, and best practice guidance that, for some time, is a commonly accepted framework within a scientific discipline or research area (Bird, 2022).

For example, a biomechanical study of movement skills from a third-person point of view offers quantified descriptions, mechanistic explanations, and predictive force. The alternative phenomenological approach examines the experiential qualities of movement skills. The methodological ideal is to describe the world as lived *(Lebenswelt)* and explore skill execution from a first-person point of view.

In Kuhnian terminology, the two approaches could be conceived as incommensurable and belong to different paradigmatic traditions (Oberheim and Hoyningen-Huene, 2018; Bird, 2022). One indication of incommensurability is that the main theoretical and methodological concepts of one approach can not be translated and applied in meaningful ways in another (Boyd, 1991). For example, references to mechanical forces in movement are not commonly used in a description of experiential qualities, and phenomenological analyses referring to experiential qualities do not make sense in a biomechanical analysis.

This is not necessarily problematic. The original Kuhnian idea of scientific revolutions, in which the hegemonic scientific paradigm is challenged and eventually replaced with a new and incommensurable paradigm, is contested. As Toulmin (1970) and later Argamakova (2018) argue, empirically speaking, few, if any, scientific breakthroughs can be explained in this way. Current grand projects in the life sciences and neuroscience build on interdisciplinary and transdisciplinary multi-paradigmatic approaches. The alternative view is that different scientific paradigms are not mutually exclusive but complementary. For example, a combination of approaches to movement skills can enhance insight and understanding of the phenomenon.

Still, there is a challenge here. What emerges as a unified phenomenon in real life – an athlete performing at a high level of skill where all movement elements are integrated into efficient wholes – is split into several explanatory and interpretative schemes. Although research necessarily builds on the reduction of complexity, separating bodies of knowledge can prevent the integration of ideas and data and thereby limiting our understanding. On the other hand, if separate bodies of knowledge are bridged and integrated, their complexity may enrich our understanding.

Historically, the natural science and phenomenological schisma reflect classic Cartesian dualism in which the body and mind belong to two separate and qualitatively different spheres of reality: extended, material, and mechanistic substance *(res extensa)*, and non-extended non-mechanistic thinking substance *(res cogitans)*. In contemporary science and philosophy of mind, dualism has lost the ground it once possessed, yet the mind–body explanatory gap remains in numerous different versions, some of which are of special relevance in this context. Let us illustrate with examples from skiing research.

Current research on movement skills: limitations and possibilities

Consider the complex movement skill in the sport of ski jumping. Athletes experience their sport as a 'contest against gravity.' A peak experience of a successful jump is the feeling of 'flying,' 'not landing,' most clearly obtained in the largest hills where athletes appear to take off again after literally having scraped the surface.

Typically, practitioners' accounts of embodied, experiential qualities play a marginal role in research. The standard approach is biomechanics. Core elements are the role of gravity, ground reaction forces, including the centripetal component in the curvature of the inrun, force development in the take-off action, and aerodynamics. From this perspective, athletes do not 'fly' but predominantly fall and glide, postponing the landing, which is possible due to the smart use of aerodynamic forces.

The reductionism of the approach, that is, the attempt to describe and explain a phenomenon in an analytic breakdown into its basic entities, limits knowledge outcomes. Anecdotally, a simulation study on the mechanics of the inrun action in ski jumping revealed a complex mathematical problem at the end of the radius when entering the straight take-off table of the ski jump (Ettema et al., 2005). In the moments before take-off, the centripetal ground reaction force component and rotation abruptly disappear. In the real world, the well-trained ski jumper has no issue with this change in condition. However, solving this issue mathematically and simulating the real world appeared difficult.

The next step of the study was to add perspectives from neural control and imperfection.[1] The ski jumping simulation indicated that the rate of muscle force generation needed to manage the transitions between radius of the middle part of the inrun and the straight ski jump while maintaining body position was beyond feasible. Nevertheless, somehow motion must occur. In real life, then, instructions like 'maintain a constant position' can become a quest for an 'undesired Utopia'. The question arises as to whether small movements by the athlete during the inrun are an imperfection, a necessity, irrelevant, or perhaps even an advantage.[2] In other words, the mechanistic approach (biomechanics) seems to miss the essential qualities of the phenomenon it aspires to explain: good ski jumping technique.[3]

Another inadequacy is the lack of conceptualization of movement skill innovation and development. The quest for performance enhancement is a core aspect of an athlete's skill training. An example from cross-country skiing is illustrative. In the early 2000s, the Swedish skier Bjørn Lind sprinted faster than any other skier in the double poling technique. A skier's movements and speed can be explained by analyzing the frequency of double poling along with cycle lengths. Lind could produce longer cycle lengths than other skiers by using the legs extensively in a forward 'jump-like movement' in the repositioning phase before he dropped his body mass on the poles in the repositioning phase. This was later described as the 'modern' double poling technique (Holmberg et al., 2005). The underlying mechanics were further investigated 10 years later. The active and rapid extension of the legs to rise and forward-rotate the center of mass increased the potential and rotational energy, in which an effective energy transfer to mechanical energy and propulsion through the poles in the subsequent poling phase would enable fast double poling speeds (Danielsen et al., 2015).

Mechanistic analyses are efficient in the critical assessment of already existing movement skills. The focus is primarily retrospective in kind. In a more comprehensive approach, insights must be integrated from actual practice in which movement creativity and innovation play important parts.

Interplay: toward a non-reductive physicalist point of view

The quest for a broader, integrative approach faces paradigmatic tensions. This concerns not only theoretical and methodological issues but metaphysical assumptions as well, among them views on the body–mind relationship and the nature of consciousness. A detailed discussion of various positions is beyond the scope of this essay. A brief review, however, is necessary to understand the premises of our further argument.

Basically, we face here what Chalmers (1995) calls 'the hard problem of consciousness': how to explain the relationship between physical phenomena, such as the neuromuscular interplay between sensory inputs in the execution of movement skills, and the subjective experience of the same execution, or 'what it is like' from a first-person point of view.[4]

Several solutions have been proposed. To a reductive physicalist, mind is matter and can be explained in mechanistic terms. For instance, if we, sometime in the future, acquire sufficient insight into the neurophysiology and biochemistry of the brain, the subjective experience of skill execution can be fully explained by chains of cause-and-effect relationships. The hard problem of consciousness does not really exist.

The position is criticized on many accounts, among them that one and the same mental state, for instance, the discomfort of anaerobic fatigue during intensive training, can have a variety of realizers of both physiological and psychological kind. To explain a particular mental state with reference to one main explanatory scheme seems impossible. More generally, reductive physicalism is limited when it comes to accounts of the extensive variability and diversity in human interpretation and sense-making. Highly motivated athletes see anaerobic fatigue as a sign of high-quality training and development. 'No pain, no gain', as the slogan goes. Others react negatively and associate fatigue not with progress but with destructive pain.

To the classical Cartesian dualist, the solution is to see mind and matter as ontologically belonging to different spheres of reality. In modern terms: Neurophysiological response and its subjective interpretation have no relation. This naturally lends itself to a dualistic epistemology, where we operate in two different worlds understood by two different paradigms – one mechanistic and one interpretive. Whilst Cartesian dualism is no longer a viable ontology in research, the latter epistemological assumptions are common in the sports sciences (Loland and McNamee, 2017). For instance, the main body of research on movement skills is anchored in a mechanistic paradigm. In a comprehensive understanding of movement skills, the exclusivity of that focus is contra-intuitive. How can intentional movement be understood if the first-person perspective is ignored?

Contemporary cognitive science is dominated by a non-reductive physicalist point of view in which mental states have their origins in physical phenomena but cannot be fully

1 "No movement in sports is done perfectly; there is always room for improvement" is a popular expression. We may expand on this, positing that it does not need to be perfect to be beautiful, and neither does the control of movement; it simply needs to work.

2 Defining 'imperfection' from a mechanistic perspective is doomed to be limited. Some movement is required to handle any perturbation in the inrun (including the abovementioned transitions), which is a positive factor. On the other hand, movement may increase aerodynamic drag, which is a negative factor. Moreover, movement may affect (control of) the take-off action, which is an undecided factor. To put it differently, when searching for optimization, scientists (Ettema et al., 2005) may interpret the practical challenge (proceeding through the inrun with high speed and in a position that allows a good jump) incorrectly, thereby 'barking up the wrong tree'.

3 Certainly, more complex mathematics that would have been able to solve the problem more elegantly exists, but such challenges arise most frequently in computer simulation and modeling. The use of integration solvers in a direct dynamics computer simulation is an example of not applying pure mathematics (algebra) when describing reality but searching for an optimal solution. Possibly, the development of artificial intelligence (AI) is the pinnacle of this 'crusade' and can provide new possibilities in this respect.

4 See Nagel (1974) who argues that the subjective character of 'what it is like' to have a certain type of experience, for instance of well-ececuted technique, escapes physical theory.

explained in simple, mechanistic terms (Changeux, 1997, 2004). Varela et al.'s (2016) study of 'the embodied mind' interprets consciousness by integrating phenomenological (and Buddhist) accounts of human experience with cognitive science. Varela et al. point to the position of 'enactivism': The living body is seen as a self-producing and self-maintaining system that enacts and brings forward relevance and meaning in the world. Embodied cognition, for instance in the execution of movement skills, finds its form in complex, senso-motoric interaction with the world.

Gallagher and Zahavi (2012) refers to the 4 E's of an enactivist approach: Cognition is not a matter of inner representations of events in the world but is embodied (anchored in senso-motoric and perceptual capabilities of the body), embedded (intentional and always directed toward objects and events of the world), enacted (focusing on affordable objects and events), and extended (emerging in a deep interaction with environmental objects and events).

As will be shown below, the recent attempt by Pokropski (2021) of phenomenological analysis as a starting point for an integration with multi-level mechanistic explanation in cognitive science provides an interesting framework for movement skill studies. In the most extensive understanding, a particular experiential quality is the tip of the iceberg of an immensely complex interplay between an individual's biology and 'lived' history from the moment of conception to the moment of performance.

What has been said so far on the need for a broader, integrative approach is in line with a non-reductive physicalist position. Even if mechanistic and phenomenological approaches differ in theoretical and methodological frameworks, they are seen as complementary ways of describing the same physical reality. However, although being broader than what is found in traditional movement analysis, our scope is not the complete mapping of all contributing factors in skill development but the far more restricted aim of examining factors with immediate and significant impact in the execution of skills.

In the last decades, non-reductive physicalist ideas have exerted impact in movement skill studies. Newell's (1986) work on the functional aspects of movement and the significance of interactions between organismic, environmental, and task constraints in coordination development has provided essential theoretical groundwork. Examples can be found in the works of Ettema and colleagues (Ettema et al., 2017, 2018, 2023; Løkkeborg and Ettema, 2020) on the impact of environmental or task constraints, such as incline, speed, and power demand, on the selection of sub-techniques in classical roller skiing. Still, there remain unanswered questions when it comes to integrating a first-person perspective. While their findings closely aligned with expectations based on the metabolic efficiency of these techniques, none of these factors could be identified as the sole controlling environmental parameter. Moreover, significant inter-individual differences were observed.

The phenomenon of hysteresis, as seen in the speed-dependent walk-run transition, was also evident in these studies. Hysteresis cannot be adequately explained solely by the concept of 'minimizing energy expenditure' but is better elucidated by dynamical systems models (e.g., Haken et al., 1985; Hommel et al., 2001). In this context, the ideas proposed by Wolpert et al. (1995), introducing the subjective comparison between intended, anticipated, and perceived results of movement, are particularly relevant. If hysteresis, essentially a delay in action, is a natural occurrence in sub-technique selection and disappears under artificial conditions (e.g., changing environmental/task constraints but not power demand), one could argue that the comparison between intended and anticipated outcomes is unnaturally influenced. It is worth noting, however, that these dynamical systems models do not seem to encompass the holistic phenomenological experience of athletes, including sensations described as 'being in rhythm' or 'in the flow.'

A final example from cross-country skiing research includes an attempt to integrate the subjective, first-person point of view. Cross-country skiing technique has been analyzed by advanced global navigation satellite systems and inertial movement unit analyses combined with heart rate measurements and video (Tjønnås et al., 2019; Seeberg et al., 2022). The objective measurements allow the determination of the speed and position of the skier, cycle rate and length, body, ski, and poling angles, the timing of the movements, and indications of the metabolic effort. Thereafter experiential qualities can be captured in a more inclusive way by the athlete subjectively describing the race and positioning, the technical solutions, and the feeling of fatigue toward the finish line. Many experiential qualities might be well correlated with the objective data, demonstrating links to mechanistic explanations. Others might deviate and challenge both explanations and the experience of the skier. But again, some (important) experiential qualities, such as those of 'flow' or 'rhythm', may not be captured. There is need for alternative approaches.

Executive knowledge: 'knowing how' versus 'knowing that'

From the non-reductive physicalist perspective, the gap between the first and third-person point of view is primarily epistemological in kind. Ryle's (1949/2009) distinction between 'knowing-that' and 'knowing-how' exemplifies this. 'Knowing-that' refers to being able to *describe and explain* a skill or competence, as in the biomechanics of successful skiing technique. 'Knowing-how' refers to the executive practical knowledge of *performing* the same skills as in actual well-performed skiing. Ryle criticizes what he sees as a dualist, 'intellectualist legend' with the implicit understanding of an ontologically independent mind, or a 'ghost in the machine', that secures successful outcomes by strict rule-following. Ryle's point is the opposite: Execution of skills precedes and is independent of its articulated explanation.

In athlete and coach communities, the primary interest is in 'knowing how' expressed in vague and generic 'tribal' terms and in instructional nudges such as 'finding the rhythm,' 'going all in,' 'being alert yet relaxed', and 'becoming one with the task'. What more can be said of 'knowing how'?

One commonly held view emphasizes automatization. At their best, skill experts perform 'without thinking'. Beilock and Carr (2001. p. 702) talk of the 'expertise-induced amnesia' hypothesis. The hypothesis finds some empirical support in Csikszentmihalyi's (2008) theory of expert 'flow'-experiences with an optimal tension between challenge and mastery and in Dreyfus et al. (1986) phenomenological-based theory of non-conceptual and smooth coping. The view is usually accompanied by the idea that if performers think critically while performing, skills break down into fragments, and performance quality decreases.[5]

In the philosophy of sport, this view has met significant critique (Moe, 2005; Breivik, 2014; Ilundáin-Agurruza, 2014; Borge, 2015; Montero, 2016; Birch, 2017). On a broader scale, Montero (2016) develops the critique and defends the alternative 'cognition-in-action' principle. Skill execution takes deliberate effort and includes critical problem-solving and self-teaching. Successful performances in fields such as dance, music, chess, and sports are characterized by clear performer intention, balanced effort, ongoing critical review and adjustment, and a quest for control. Negative and unpleasant thoughts are 'washed away'.

Recent insights into the functioning of the brain provide empirical support to skill execution as various modes of deliberate and cognitive action. In their review of current research, and pointing to the work of, among others, J.-P. Changeux and G. W. Edelman, Farisco et al. (2017) portray the brain as a complex, dynamic, and plastic organ that is spontaneously active and predisposed to be projective in the evaluation and modeling of the world. Brain architecture opens for '…a complex flow of feedforward and feedback loops' in explicit and aware as well as in implicit and unaware functional modes (Farisco et al., 2017, p. 2015).

Borge's (2015, p. 125) distinctions between three modes of knowing how to do a sport seem to follow this line of reasoning. There is reflective awareness of knowing-how (as in Montero's 'cognition in action'), in-zone awareness of knowing-how (as in Csikszhentmihalyi's *flow*), and even zoned-out awareness of knowing-how (as during the transportation stretches of a skiing race in which the racers are in control without focusing on the execution of their skiing technique). Bergamin (2017) and Christensen et al. (2016) portray a view of skilled action in which these modes of skill execution are 'meshed' and overlap and interact:

> Automation has clear benefits for skill control: the integration and simplification of action control can make action production more efficient. But cognitive control nevertheless makes a vital contribution to skill control by determining the nature of the situation and configuring and adjusting lower-order sensorimotor processes appropriately. Cognitive and automatic processes thus characteristically operate together in an intimately meshed arrangement, with cognitive control typically focused on strategic task features and automatic control responsible for implementation.

The reference to sensorimotor processes indicates that this 'meshed arrangement' is closely connected with the proprioceptive sense.

Proprioception and experiential qualities

In Montero's (2016) view, *proprioception,* sometimes used synonymously with kinaesthesia, or the kinesthetic sense plays a core role. In Han et al.'s (2016) definition, the proprioceptive sense is '…an individual's *ability* to integrate the sensory signals from mechanoreceptors to thereby determine body segment positions and movements in space'. More generally, the proprioceptive sense is defined as part of the somatosensory system and enables stability, accuracy, and efficiency in the solving of movement tasks by combining multiple inputs to the CNS from muscle and connective tissue receptors, as well as information from the vestibular system and the exteroceptive senses: vision, sound, and touch.

Proprioception is defined and explained not just physiologically but psychologically and contextually with impact from personality, sex, age, and situational factors such as the intensity and stress of a competitive situation. Montero (2016, p. 121) extends this perspective even further. In her view, proprioception is not just '…the sense by which we acquire information about the positions and movements of our bodies', it is also '…an aesthetic sense, that is, a sense by means of which we experience beauty, grace, and other aesthetic properties'. Proprioception includes the phenomenological grasping of conceptualizable aesthetic experiences.

It should be noted that what is of interest is not the individual athlete's subjective experience of a movement skill but the experiential, proprioceptive qualities that characterize the successful execution of the skill itself, its invariant and demarcating qualities in practice, so to speak. Montero's core example is dance, where the many and various techniques have strict, intersubjective, and detailed prescriptions and where expressive, aesthetic elements play a key role. Examples from skiing can be the feel of perfect timing of the take-off in ski jumping or the sense of optimal power utilization in a double-poling sprint. The important point is that experiential qualities are representational: they are intersubjective qualities of lived practice that can be articulated and examined critically.

Insights into the experiential skill qualities are found not only among performers but in experienced observers as well. Discussing competent dance critics, Montero (2016, p. 201) talks of their reference to 'kinaesthetic sympathy.' In a similar vein, experiential qualities of sports skills are matters of shared understanding of both athletes and coaches and probably a key to their successful interaction.[6]

Whereas the practitioners' language in dance deals with aesthetic qualities, 'tribal' coach and athlete language is influenced by biomechanics. In his study of alpine skiing technique, Loland (1992, 2008) has explored possible interconnections between experiential qualities and mechanistic explanations. Terms such as 'being in balance,' 'finding support on the surface,' and 'optimal gliding' can be operationalized in a series of detailed prescriptions on the use of hip

5 Anecdotally, and according to expert support staff, about half of Norwegian elite ski jumpers have no recollection of the take-off action right after the performance (having landed).

6 There is a connection here to Rizzolatti and collaborators' hypothesis in neuroscience of 'the human mirror system' – or of an in-built 'action-observation network' (Birch, 2017). When observing motor action, specialized mirror neurons in the brain exhibit increased activity. Research in monkeys relates to basic motor action: grasping, touching, *et cetera*. It can be hypothesized that similar activation takes place in humans and that the mirroring function plays a role in the learning and critical evaluation of movement skills. This provides further empirical evidence for a non-dualist approach to understanding skill execution (Birch, 2017) and may have interesting practical implications, among them as a rationale for imitation as a main didactic approach in skill learning (Watanabe et al., 2017).

and knee angling, and adaptive ski edging. Loland argues that most references to experiential qualities have their biomechanistic equivalents and can be translated into a mechanistic framework, thus suggesting complementarity. Balance deals with equilibrium conditions, and support from the surface and gliding with the efficient utilization and optimization of frictional forces. As with the dynamical systems approach, however, the integrating element, phenomenologically referred to as the pre-reflective and holistic sense of movement rhythm in which the execution of skills is experienced as a functional whole, seems to evade analytic operationalization. What can be done?

Toward an integrative approach

Pokropski' (2021) work on integrating phenomenology with cognitive science offers possibilities. Phenomenology is used to give an initial description of the phenomenon under study and provide constraints for exploring relevant mechanistic explanations. We take inspiration in Pokropski's approach in our outline three steps of integrative approach to movement skills.

The first step is to articulate and tentatively decompose the experiential qualities of good technique. To be able to grasp essential qualities, expert movement ought to be studied *in situ* and with reference to practitioners' sense and understanding. There is a need for a phenomenological methodology to describe the experts' life world (*Lebenswelt*): the directly perceived, pre-theoretical experience of executing movement skills. This is the first-person perspective of the sensorily engaged 'lived body' operating in a perceptual field of numerous actual and potential interconnections (Merleau-Ponty, 2012). Montero's (2016) descriptions of proprioception in dance, and Loland's (2008) the experiential qualities of alpine skiing, are inspired by phenomenological descriptions of this kind.

With this first step, functional and dynamic constraints can be identified, creating a space for the search for further analyses and mechanistic explanations (Pokropski, 2021, 139 ff.). *Functional constraints* are found by decomposing the skill under study into its constitutive elements or defining its 'functional architecture', so to speak. For example, in Loland's analysis, the experience of well-executed alpine skiing technique is decomposed into three main technical elements: being in balance, finding support on the surface, and smooth and effortless gliding. In our interpretation here, *dynamical constraints* refer to how these qualities emerge and play out temporally in skill execution. Phenomenologically, Loland refers to the holistic experiential quality of movement rhythm or movement flow.

The functional and dynamic constraints provide critical criteria in the search for possible mechanistic explanations. We are now at *the second step* of the integrative approach. The aim is not to integrate phenomenology into a well-defined nomological framework as found in classical biomechanics but to explore a patchwork of multilevel explanations from multiple research fields (Pokropski, 2021, 79 ff.). For instance, being in balance can be explained with reference to biomechanical analysis of dynamic stability and/or motor control approaches based on dynamical systems theory. Finding support on the surface and smooth gliding implies the efficient use of frictional forces. Again, biomechanics and motor control approaches are of relevance. In addition, expert skiers' fine-tuned sense for gliding and optimizing frictional forces require additional insights from, say, the neuroscience of proprioception. Movement rhythm understood phenomenologically refers to a holistic whole that is bigger than the sum of its parts. Relevant explanations can be found in cognitive science and in insights into the brain's spontaneous and adaptive capabilities in evaluating and modeling the world 'in action', and from expertise studies discussed in detail in Montero's (2016).

The integration of experiential qualities and mechanistic explanations is a critical and explorative exercise. The attempt is to describe and explain 'lived' skill execution. As is evident from the ski jumping simulation study discussed above (Ettema et al., 2005), there is no hierarchical ordering here in which 'incomplete' phenomenology is converted into 'complete' scientific analysis. Phenomenological accounts of a skill can also lead to the revision of empirical hypotheses and choice of explanations. The integrative process is holistic in nature.

A third step implies using the outcome of step two in the systematic theory building of skill patterns. This is an exercise of connecting and bridging key concepts and explanations in complementary and consistent ways. A systematic overview of the phenomenological structure of a skill and its multilevel mechanistic explanations constitute a theory of this skill. Integrative approaches give rise to *specific skill theories*. With their starting point in experiential qualities of actual skill execution and the explorative approach into multi-level relevant mechanisms, specific skill theories are different from and can complement theories developed within stricter nomological structures. An integrative approach connects the first-person 'lived' perspective with the third-person perspective of mechanistic science.

Concluding comments

We started this article by describing the need for a broader and integrated understanding of movement skills in sports that potentially bridges the gap between accounts of experiential qualities in practice and theoretical explanation. By starting from Kuhn's idea of paradigms, using practical cases from skiing research and approaches as those found in among others Montero and Pokropski, we have sketched three steps of an integrative approach. Moreover, we have argued that the integrative approach can lead to sport-specific movement skill theories that complement traditional nomological movement science and strengthen the practical relevance of research.

Our outline is no 'quick fix' solution to bridging the theory-practice gap. Pokropski's (2021) account of integrating phenomenology with cognitive science needs critical review and development (Ward, 2022; Madary, 2023). The very idea of integration is contested by critics who define phenomenology as a philosophical, transcendental perspective. Moreover, traditionally, scientific explanation is anchored in precise and conceptually clear theoretical frameworks. Attempts on explaining a skill with a pluralistic system of multilevel mechanistic explanations may seem challenging. No doubt, the integrative approach would require open-minded and multidisciplinary research efforts, substantial data processing power, and the exercise of a core scientific virtue: the non-reductive reduction of complexity.

The rewards might be worth the effort, however. Kuhn (1962/1996) argues that innovative insights and paradigmatic change often originate and develop at the margins of established scientific milieus. With its relatively short history and practical orientation, the sports sciences are at these margins. Further research along the lines of the integrative approach may lead to more innovative ways of understanding human skill execution. Expanding the perspective, the study of movement skills might be well-suited to shed new light on far more extensive questions, such as the nature of body–mind interaction and the nature of human consciousness.

Author contributions

SL drafted and wrote the article with contributions from GE and ØS.

Acknowledgments

The authors want to thank two reviewers and professor Kathinka Evers for valuable critique and comments.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Argamakova, A. (2018). "Modeling scientific development: lessons from Thomas Kuhn" in *The Kuhnian image of science: time for a decisive transformation?* ed. M. Mizrahi (London: Rowman & Littlefield), 45–59.

Beilock, S. L., and Carr, T. H. (2001). On the fragility of skilled performance: what governs choking under pressure? *J. Exp. Psychol. Gen.* 130, 701–725. doi: 10.1037/0096-3445.130.4.701

Bergamin, J. A. (2017). Being-in-the-flow: expert coping as beyond both thought and automaticity. *Phenomenol. Cognit. Sci.* 16, 403–424. doi: 10.1007/s11097-016-9463-1

Birch, J. E. (2017). Intentional and skillful neurons. *Sport Ethics Philosophy* 11, 339–356. doi: 10.1080/17511321.2017.1334695

Bird, A. (2022). "Thomas Kuhn" in *The Stanford encyclopedia of philosophy*. ed. E. N. Zalta Available at: https://plato.stanford.edu/archives/spr2022/entries/thomas-kuhn/

Borge, S. (2015). "Epistemology and sport" in *Routledge handbook of the philosophy of sport*. eds. M. McNamee and W. J. Morgan (London: Routledge), 115–130.

Boyd, R. (1991). "Confirmation, semantics, and the interpretation of scientific theories" in *The philosophy of science*. eds. R. Boyd, P. Gasper and J. D. Trout (Cambridge MA: Bradford), 5–35.

Breivik, G. (2014). Sporting knowledge and the problem of knowing how. *J. Philos. Sport* 41, 143–162. doi: 10.1080/00948705.2014.911102

Chalmers, D. J. (1995). Facing up to the problem of consciousness. *J. Conscious. Stud.* 2, 200–219.

Changeux, J.-P. (1997). *Neuronal man. The biology of mind*. New York: Princeton University Press.

Changeux, J.-P. (2004). *The physiology of truth. Neuroscience and human knowledge*. Cambridge, MA: Belknap, Harvard University Press.

Christensen, W., Sutton, J., and McIlwain, D. J. F. (2016). Cognition in skilled action: meshed control and the varieties of skill experience. *Mind Lang.* 31, 37–66. doi: 10.1111/mila.12094

Csikszentmihalyi, M. (2008). *Flow: the psychology of optimal experience*. London: Harper.

Danielsen, J., Sandbakk, Ø., Holmberg, H. C., and Ettema, G. (2015). Mechanical energy and propulsion in ergometer double poling by cross-country skiers. *Med. Sci. Sports Exerc.* 47, 2586–2594. doi: 10.1249/MSS.0000000000000723

Dreyfus, H. L., Dreyfus, S. E., and Athanasiou, T. (1986). *Mind over machine: the power of human intuition and expertise in the era of the computer*. New York: Free Press.

Ettema, G., Bråten, S., and Bobbert, M. F. (2005). Dynamics of the in-run in ski-jumping: a simulation study. *J. Appl. Biomech.* 21, 247. doi: 10.1123/jab.21.3.247

Ettema, G., Kveli, E., Øksnes, M., and Sandbakk, Ø. (2017). The role of speed and incline on the spontaneous choice of technique in classical roller-skiing. *Hum. Mov. Sci.* 55, 100–107. doi: 10.1016/j.humov.2017.08.004

Ettema, G., Øksnes, M., Kveli, E., and Sandbakk, Ø. (2018). The effect of exhaustive exercise on the choice of technique and physiological response in classical roller skiing. *Eur. J. Appl. Physiol.* 118, 2385–2392. doi: 10.1007/s00421-018-3965-1

Ettema, G., Skovereng, K., Ritman, T., and Danielsen, J. (2023). The role of external power demand on the choice of technique in classic cross-country skiing. *PLoS One* 18:e0283794. doi: 10.1371/journal.pone.0283794

Farisco, M., Laureys, S., and Evers, K. (2017). The intrinsic activity of the brain and its relation to levels and disorders of consciousness. *Mind Matter* 15, 197–219.

Gallagher, S., and Zahavi, D. (2012). *The phenomenological mind*. London: Routledge. *2nd*

Haken, H., Kelso, J. A. S., and Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biol. Cybern.* 51, 347–356. doi: 10.1007/BF00336922

Han, J., Waddington, G., Adams, R., Anson, J., and Liu, Y. (2016). Assessing proprioception: a critical review of methods. *J. Sport Health Sci.* 5, 80–90. doi: 10.1016/j.jshs.2014.10.004

Holmberg, H. C., Lindinger, S., Stöggl, T., Eitzlmair, E., and Müller, E. (2005). Biomechanical analysis of double poling in elite cross-country skiers. *Med. Sci. Sports Exerc.* 37, 807–818. doi: 10.1249/01.mss.0000162615.47763.c8

Hommel, B., Müsseler, J., Aschersleben, G., and Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behav. Brain Sci.* 24, 849–937. doi: 10.1017/s0140525x01000103

Ilundáin-Agurruza, J. (2014). Waking up from the cognitivist dream—the computational view of the mind and high performance. *Sport Ethics Philos.* 8:343. doi: 10.1080/17511321.2015.1027465

Kuhn, T. (1962/1996). *The structure of scientific revolutions*. Chicago: University of Chicago Press. *3rd*

Løkkeborg, J., and Ettema, G. (2020). The role of incline, speed and work rate on the choice of technique in classical roller skiing. *PLoS One* 15:e0236102. doi: 10.1371/journal.pone.0236102

Loland, S. (1992). The mechanics and meaning of alpine skiing. Methodological and epistemological notes on the study of sport technique. *J. Philos. Sport* 19, 55–77. doi: 10.1080/00948705.1992.9714495

Loland, S. (2008). "Alpine skiing technique - practical knowledge and scientific analysis" in *Science and skiing IV*. eds. E. Müller, S. Lindinger and T. Stöggl (Meyer & Meyer Sport: Aachen), 43–58.

Loland, S., and McNamee, M. (2017). Philosophical reflections on the mission of the European College of Sport Science: challenges and opportunities. *Eur. J. Sport Sci.* 17, 63–69. doi: 10.1080/17461391.2016.1210238

Madary, M. (2023). Review of Marek Pokropski's mechanisms and consciousness: integrating phenomenology with cognitive science. *Husserl Stud.* doi: 10.1007/s10743-023-09327-7

Merleau-Ponty, M. (2012). *Phenomenology of perception*. London: Routledge

Mizrahi, M. (ed.) (2018). *The Kuhnian image of science: time for a decisive transformation?* London: Rowman & Littlefield.

Moe, V. F. (2005). A philosophical critique of classical cognitivism in sport: from information processing to bodily background knowledge. *J. Philos. Sport* 32, 155–183. doi: 10.1080/00948705.2005.9714680

Montero, B. G. (2016). *Thought in action: expertise and the conscious mind*. Oxford: Oxford University Press.

Nagel, T. (1974). What is it like to be a bat? *Philos. Rev.* 83, 435–450. doi: 10.2307/2183914

Newell, K. M. (1986). "Constraints on the development of coordination" in *Motor development in children*. eds. M. G. Wade and H. T. A. Whiting (Amsterdam: Martinus Nijhoff), 341–360.

Oberheim, E., and Hoyningen-Huene, P. (2018). "The incommensurability of scientific theories" in *The Stanford encyclopedia of philosophy*. ed. E. N. Zalta Available at: https://plato.stanford.edu/archives/fall2018/entries/incommensurability/

Pokropski, M. (2021). *Mechanisms and consciousness. Integrating phenomenology with cognitive science*. London Taylor & Francis Books

Ryle, G. (1949/2009) *The concept of mind*. Oxon: Routledge

Seeberg, T. M., Kocbach, J., Kjøsen Talsnes, R., Meyer, F., Losnegard, T., Tjønnås, J., et al. (2022). Performance effects of video-and sensor-based feedback for implementing a terrain-specific micropacing strategy in cross-country skiing. *Int. J. Sports Physiol. Perform.* 17, 1672–1682. doi: 10.1123/ijspp.2022-0106

Tjønnås, J., Seeberg, T. M., Rindal, O. M. H., Haugnes, P., and Sandbakk, Ø. (2019). Assessment of basic motions and technique identification in classical cross-country skiing. *Front. Psychol.* 10:1260. doi: 10.3389/fpsyg.2019.01260

Toulmin, S. (1970). "Does the distinction between normal and revolutionary science hold water?" in *Criticism and the growth of knowledge*. eds. I. Lakatos and A. Musgrave (London: Cambridge University Press), 39–47.

Varela, F. J., Thompson, E., and Rosch, E. (2016). *The embodied mind. Cognitive science and human experience*. Cambridge, MA The MIT Press (*Revised edition*).

Ward, D. (2022). Marek Pokropski: mechanisms and consciousness. Integrating phenomenology with cognitive science. Notre dame philosophical reviews. Available at: https://ndpr.nd.edu/reviews/mechanisms-and-consciousness-integrating-phenomenology-with-cognitive-science/

Watanabe, R., Higuchi, T., Kikuchi, Y., and Taira, M. (2017). Visuomotor effects of body part movements presented in the first-person perspective on imitative behavior. *Hum. Brain Mapp.* 38, j6218–j6229. doi: 10.1002/hbm.23823

Wolpert, D. M., Ghahramani, Z., and Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science*, 269, 1880–1882. doi: 10.1126/science.7569931

Check for updates

OPEN ACCESS

EDITED BY
Karen Zentgraf,
Goethe University Frankfurt, Germany

REVIEWED BY
Mu Qiao,
Louisiana Tech University, United States
Björn Wieland,
Goethe University Frankfurt, Germany

*CORRESPONDENCE
Jason Friedman
✉ jason@tauex.tau.ac.il

RECEIVED 27 August 2023
ACCEPTED 19 October 2023
PUBLISHED 13 November 2023

CITATION
Geller N, Moringen A and Friedman J (2023) Learning juggling by gradually increasing difficulty vs. learning the complete skill results in different learning patterns.
Front. Psychol. 14:1284053.
doi: 10.3389/fpsyg.2023.1284053

Learning juggling by gradually increasing difficulty vs. learning the complete skill results in different learning patterns

Noga Geller[1], Alexandra Moringen[2,3] and Jason Friedman[1,4]*

[1]Department of Physical Therapy, School of Health Professions, Faculty of Medicine, Tel Aviv University, Tel Aviv, Israel, [2]Neuroinformatics Group, Bielefeld University, Bielefeld, Germany, [3]Institute for Data Science, Greifswald University, Greifswald, Germany, [4]Sagol School of Neuroscience, Tel Aviv University, Tel Aviv, Israel

Motor learning is central to sports, medicine, and other health professions as it entails learning through practice. To achieve proficiency in a complex motor task, many hours of practice are required. Therefore, finding ways to speed up the learning process is important. This study examines the impact of different training approaches on learning three-ball cascade juggling. Participants were assigned to one of two groups: practicing by gradually increasing difficulty and elements of the juggling movement ("learning in parts") or training on the complete skill from the start ("all-at-once"). Results revealed that although the all-at-once group in the early stages of learning showed greater improvement in performance, the "learning in parts" group managed to catch up, even over a relatively short period of time. The lack of difference in performance between the groups at the end of the training session suggests that the choice of training regime (between all-at-once and learning in parts), at least in the short term, can be selected based on other factors such as the learner's preference, practical considerations, and cognitive style.

KEYWORDS

juggling, motor learning, coordination, learning strategies, difficulty

1. Introduction

Motor skills are an essential component of the expertise displayed by, and required of, individuals working in medicine or other health professions, as well as the basis for many human cultural achievements, from sports to art to music. Motor learning is typically defined as a relatively permanent change in a person's capability to perform a skill as a result of practice (Wulf, 2012). The amount of practice needed for motor skill development to achieve a high level of proficiency is dependent on the complexity of the task and can require up to thousands of hours of practice (Pritchard and Taylor, 2022). Therefore, finding effective and efficient training methods that can speed up the motor learning process are an important motivation for many researchers (Zacks and Friedman, 2020).

Motor learning is central to sport and exercise contexts and entails learning and refining skills through practice (Daumiller et al., 2021). In this experiment, three-ball cascade juggling was selected as a means to test motor learning, because it requires training and engagement of complex motor skill activities that are similar to real sports performance (Morita et al., 2016). Juggling requires simultaneous control of multiple movements, a high level of bimanual eye-hand coordination according to the visual information that is perceived, stimulating the brain areas engaged in effortful processing challenges as in open-skill sport (Berchicci et al., 2017). According to Gentile's taxonomy (Gentile, 1990), juggling would be described as having environmental constraints of motion with intertrial variability, and to have body stability requiring manipulation.

Variability throughout the learning process has been shown to enhance learning and performance in some studies. This can be achieved by practicing different variations of the same activity or changing the task difficulty (Raviv et al., 2022). A recent study compared learning complex upper-limb movements by practicing individual movement elements or practicing the entire trajectory. The control group in the experiment learned the full complex skill, whereas two other groups learned two different movement elements of the complete skill. The results demonstrated that training on a movement element benefited the performance of the full trajectory, the two groups who learned different elements showed similar improvements in the performance of the complex motor skill, despite training on different movement elements of the same complex movement. The findings show that complex movements can be learned by practicing their movement elements (Shaikh et al., 2023). Other studies have shown mixed results regarding whether part or whole practice is more beneficial (Sattelmayer et al., 2016). In this review of medical education, they did not find an overall significant difference between the learning strategies. Another study suggested subdividing the strategy of part practice into a number of subcategories, including "increasing difficulty" (Wickens et al., 2012), which is most relevant for learning juggling. In this meta-analysis, they found that increasing difficulty can be a good strategy for learning when the increase in difficulty occurs adaptively for each participant.

For successful learning, the role of the learner's motivation and feeling of success is significant. In a previous experiment in golf-putting, enhancing learners' expectancies by providing a relatively "easy" performance criterion for good performance relative to a more difficult one led to more effective learning of a golf-putting task (Palmer et al., 2016). In this experiment, we compared learning in easier difficulty levels that progress to full skill difficulty with learning the task from the start at the full skill difficulty.

In our experiment, we compared acquiring three balls cascaded juggling skills between two groups - one group learned at increasing difficulty levels through practicing elements of the full movement, while the other group learned the full complex movement at one consistent difficulty level. We predict that in the early stages of training, the group that practices the whole movement will perform better, but at the end of the session, the group that practices learning in parts will overtake their performance.

2. Methods

2.1. Participants

We recruited 40 participants from the student population at the Tel Aviv University campus through flyers placed around the campus and Facebook groups. Each participant came to the lab for a single visit of approximately 1 h. The inclusion criteria were: age 18–35, and right-hand dominant. The exclusion criteria were: ADHD diagnosis or previous juggling experience.

2.2. Equipment

The experiment was performed with three standard juggling balls. To ensure accurate counts, the participants were filmed using a GoPro Hero 7 camera for later analysis.

2.3. Experiment protocol

The participants were randomly assigned to one of two groups in a counter-balanced manner, which varied only in the type of training provided – learning in parts, or all-at-once. The experimental protocol is summarized in Figure 1.

Before and after each training period, the participants performed a juggling test with three balls for 1 min, repeated three times. Participants began the test while holding two balls in their right hand and one ball in their left hand. A successful three-ball juggling cascade catch was defined as follows: participants started by throwing one of the balls from the right hand diagonally across their body to the other side. As the ball reached its peak height, they threw the second ball from their left hand to the opposite side and caught the first ball. As the second ball reached its peak, they threw the third ball to the opposite side and caught the second ball. Finally, they caught the third ball. Participants earned one point for every set of three successful throws and catches, as described above, and additional points for each subsequent catch beyond the initial three. For example, if they successfully made four consecutive throws and catches, they received two points, and if they achieved five, they received three points, and so on. The total number of points for each test interval was calculated based on the cumulative number of successful catches within the one-minute juggling period. To account for potential variability in performance, participants performed the juggling test three times within each interval. The median value of the points from these three repetitions was used to determine their overall performance. The median is a statistical measure that identifies the middle value when data points are arranged in order, which can be more robust against outliers than taking the mean. The tests were recorded using a camera to confirm the counts during the tests, and the videos were solely used for this purpose.

The training consisted of three stages, each 13 min long that included 2 min of watching a video with instructions from a Youtube video "Learn to JUGGLE 3 BALLS - Beginner Tutorial" (Glenn, 2019), 1 min of going over the instructions together with the research assistant, 9.5 min of practicing juggling and 30 s rest while seated before the next test.

Details of which parts of the video were played are provided in the Supplementary material. The learning in parts group received three different sets of instructions:

1. **Juggling with one ball:** Aim for the upper corner on the opposite side of the hand that is throwing the ball and throw the ball above eye height. Keep your forearm parallel to the ground. Throw the ball vertically so that it stays close to your body.
2. **Juggling with two balls:** Start by throwing the ball in your right hand. When the first ball starts to lose height, throw the second ball. Aim with the balls for the same height above eye

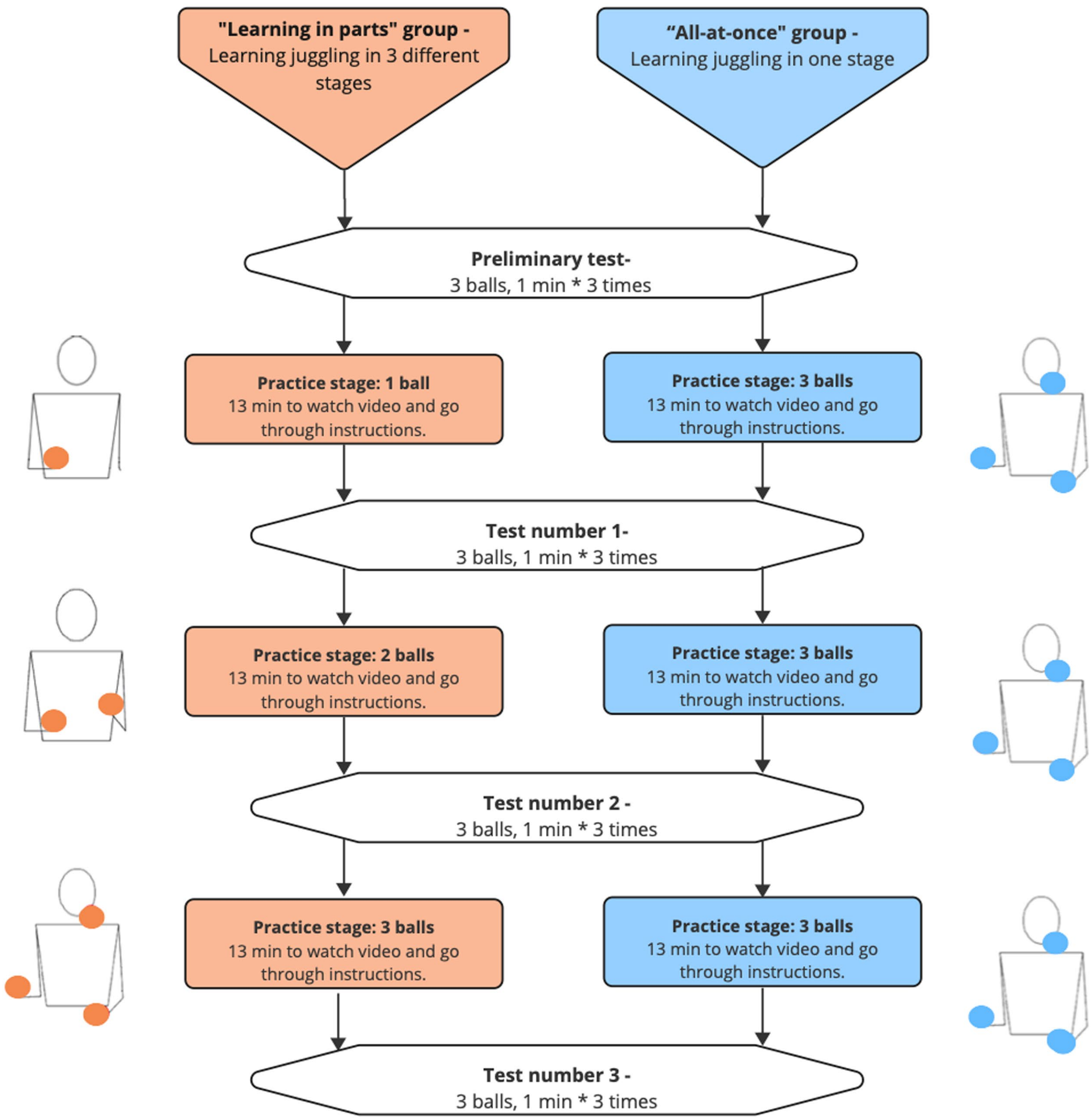


FIGURE 1
Outline of the experimental protocol. There were 20 participants in each group.

level. Throw the balls vertically so that they stay close to the body. To create a fixed rhythm between the balls, throw the second ball at the same time in every repetition, such that you throw the ball when the first ball starts to lose height. After enough repetitions, practice starting by throwing from the left hand.

3. **Juggling with three balls:** Initially, you should have two balls in the right hand. Start by throwing one of the balls from the right hand. Aim for the upper corner on the opposite side from the throwing hand and throw above eye height. Keep your forearm parallel to the ground. When the first ball starts to lose height, throw the ball from your left hand in the same manner. When the second ball starts to lose height, throw the third ball from your right hand. Throw the balls vertically so they stay close to each other. In order to maintain a fixed rhythm, throw the second ball at the same time each cycle so that the next ball is thrown when the previous ball starts to lose height.

The all-at-once training group received the third instruction above in each of the three training sessions. In the experiment, the participants were instructed in Hebrew, the instructions provided here are a translation. The original Hebrew instructions can be found in the Supplementary material.

All participants signed an informed consent form before starting the experiment, and the experiment received ethical approval from and was run according to the guidelines of the Tel Aviv University Institutional Review Board (IRB). The participants received payment for their participation.

2.4. Statistical analysis

The demographic details (age, sex) between the groups were compared using an independent samples t-test and a chi-squared test, respectively. The test scores at baseline and in the three test sessions between the two groups was compared using a non-parametric mixed-design ANOVA (F1-LD-F1 design, with the ANOVA-type statistic) with a between-subjects factor of group, and a within-subjects factor of test (baseline, and tests 1–3). F1-LD-F1 refers to a longitudinal (LD) design with 1 whole-plot factor (F1 – i.e., between-subjects - in this case group), and one subplot factor (F1 – i.e., within-subjects - in this case test) (Noguchi et al., 2012). As a measure of effect size, we used the non-parametric "measure of stochastic superiority," which we denote as A (Vargha and Delaney, 2000; Marmolejo-Ramos et al., 2013). This measure is defined as the probability that a sample taken from one condition/group will be greater than a sample randomly taken from the other condition/group. The values range from 0.5 to 1, with 0.56 considered a small effect size, 0.64 a medium effect size, and 0.71 a large effect size (Vargha and Delaney, 2000). Non-parametric analyses were used because some of the participants had scores of 0, hence the data cannot be normally distributed. The statistical analysis was performed using R (R Core Team, 2023) with the nparLD package (Noguchi et al., 2012). p values for the post-hoc tests were corrected using the Holm method.

3. Results

Forty participants took part in the experiment divided into two groups (Learning in parts: 10 males, 10 females, mean ± SD age 25.40 ± 3.87; all-at-once: 10 males, 10 females, mean ± SD age 25.65 ± 3.92). We did not observe a significant difference in age between the groups [t (38) = −0.217, p = 0.829]. The chi-squared test did not show a significant difference in the number of male or female participants between the groups [χ^2 (1) = 0.0, p = 1.0].

The outcomes of the tests are shown In Figure 2. A main effect was observed for test [F (1.652) = 38.5, p < 0.001]. Note that the degrees of freedom are not integers because the nparLD package uses Box-type approximations for estimating the distribution of the ANOVA-type statistics (Brunner et al., 1997). Post-hoc tests showed that the score on test 3 (median 6, IQR 1–19.25) was greater than in test 2 [median 5.5, IQR 0–13.25; F (1) = 15.6, p < 0.001, A = 0.74], which in turn was greater than in test 1 [median 1.5, IQR 0–10; F (1) = 27.4, p < 0.001, A = 0.78], which was greater than the score at baseline [median 0, IQR 0–3.25; F (1) = 18.3, p < 0.001, A = 0.69]. A main effect of group was not observed [F (1) = 0.028, p = 0.87]. An interaction of test and group was observed [F (1.65) = 3.64, p = 0.034]. Post hoc tests, after the Holm correction, showed that a significant difference between baseline and test 1 was observed only for the all-at-once group (baseline: median 0, IQR 0–1; test 1: median 2, IQR 0–10.5, p < 0.001, A = 0.78) and not for the learning in parts group (baseline: median 0.5, IQR 0–4.25; test 1: median 1, IQR 0–6.25, p = 0.14, A = 0.6). Both groups showed a significant improvement between test 1 and test 2 [all-at-once: test 2: median 6, IQR 0–16, p = 0.015, A = 0.8; learning in parts: test 2: median 5.5, IQR 0–10.25, p = 0.002, A = 0.75]. Between test 2 and test 3, a significant difference was only observed for the learning in parts group [test 3: median 7, IQR 1.75–22.25, p = 0.001, A = 0.83] and not for the all-at-once group [test 3: median 5.5, IQR 0.75–18.25, p = 0.114, A = 0.65]. We also note that by test 3, no significant difference was observed between the groups [Mann–Whitney test, W = 197, p = 0.95, A = 0.55].

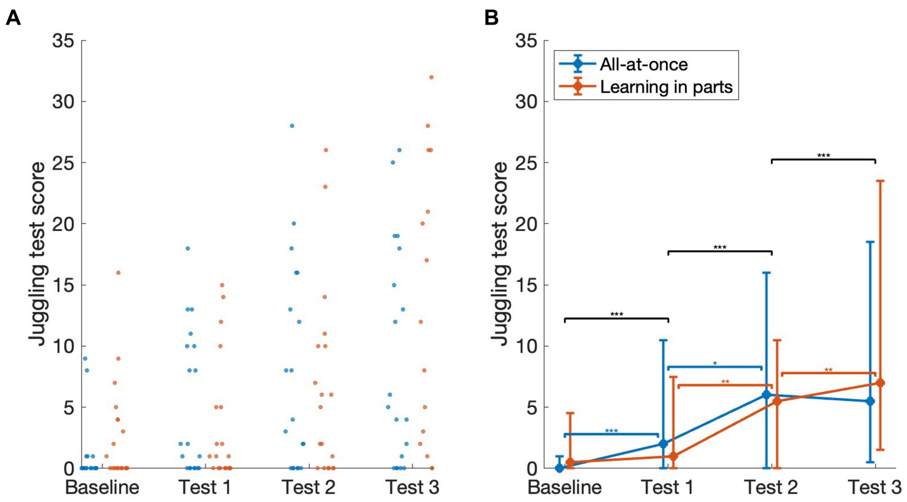


FIGURE 2
Juggling test scores of the participants in the two groups, for the baseline test and the three follow-up tests. **(A)** Juggling test scores for all subjects. For clarity, two outliers are not shown (although they were included in the statistical analysis), a graph including the outliers can be found in the Supplementary material. The data is jittered in the left–right direction to show all data points **(B)**. The medians (filled circles) and interquartile ranges (error bars) for the two groups, summarizing the data from graph **(A)**. The black horizontal bars indicate significant differences across all subjects pooled together (i.e., a main effect of test), while the blue and red bars indicate significant differences between consecutive tests for the all-at-once and learning in parts groups, respectively – the differences between the groups explain the observed interaction of test and group. *indicate p < 0.05; **indicates p < 0.01; ***indicates p < 0.001.

4. Discussion

In this study, we examined how differences in training affect learning outcomes in a juggling task. Analysis of the results revealed that either learning to juggle three balls all-at-once, or learning by gradually increasing the difficulty and number of balls showed distinctive learning patterns, with the group learning in parts initially lagging behind but eventually catching up to the group learning all-at-once. While the group practicing the complete movement initially showed more improvement, the learning-in-parts group closed the performance gap by the end of the last test. By the end of the training session, we did not observe significant differences in performance between the groups.

In a classic experiment comparing part practice to whole practice in juggling, it was found that whole practice led to faster learning to a criterion (100 consecutive catches) than part learning (Knapp and Dixon, 1952). It should be noted that this difference was found only at $p = 0.1$, and that the Student t-test used was likely inappropriate for the data (which, based on the mean and standard deviation presented, was highly likely not to be normally distributed). Additionally, the instructions in this experiment were different from the Knapp and Dixon study, which included practice with no balls and consisted of 5 min of practice per day until they succeeded in reaching the criterion (which took up to 36 sessions). These experimental differences make it difficult to compare the two studies. In children, the choice of whole vs. part learning in juggling differed as a function of age – younger children performed better with part practice, whereas older children performed better with whole practice (Chan et al., 2015). The authors suggest that these differences may result from differences in neural maturity, information-processing ability, and motor coordination as children develop.

Consistent with the experiment's hypothesis, the "learning in parts" group exhibited a comparatively lower improvement at the beginning of the experiment during the first test, as opposed to the all-at-once group. This outcome may be explained by the principle of Specific Adaptation to Imposed Demands (SAID), that asserts the human body adapts in very specific ways to the types of stresses we apply to them during our training, whether biomechanical or neurological. The SAID principle suggests that the more similar the training is to the desired skill, the more transferable the improvements will be to that skill (Sevier, 2000). In this experiment, the principle of specificity suggests that learning the complete 3 balls cascade juggling may lead to greater initial improvements because it closely aligns with the actual task of juggling that is tested.

However, the "learning in parts" group managed to catch up to the all-at-once group, even over a relatively short period of time. This can be explained by the different aspects of motor learning. One potential explanation is related to the concept of variability of practice. The learning in parts training group engaged in practicing different elements of the juggling movement at various difficulty levels. This variability in practice may have led to enhanced cognitive processing and adaptability (Raviv et al., 2022). However, the lack of difference between groups suggests that either strategy is effective, at least in terms of short-term training. The implication of this is that the type of training to use can be based on other considerations. Future studies may help understand also whether part training leads to more effective transfer (e.g., to four-ball juggling) than whole training (Wickens et al., 2012).

It should be noted that the results suggest that perhaps if the experiment had been conducted over a longer duration, whether through more extended practice time, or additional sessions with the participants, we might have observed an even greater improvement in the learning in parts group compared to the all-at-once group. Studies of juggling over longer time scales have shown that different participants show different learning curves (Qiao, 2021), where most of the participants showed an S-shape curve, where the rate of learning starts off relatively slowly, then accelerates, and finally decelerates before reaching a plateau. Furthermore, the motivation and feeling of success experienced by the parts training group in the training stages may have played a significant role. The concept of providing a relatively easy performance criterion, as seen in previous studies, could have encouraged a sense of accomplishment and positive reinforcement among the participants (Palmer et al., 2016).

Despite the fact that all participants selected for the experiment declared no prior knowledge of juggling and age differences were relatively small, there was a significant heterogeneity among the results of the participants, even on the baseline test. The varied results may have arisen from the fact that humans vary considerably in their ability to perform and learn new motor skills, and tasks such as juggling are highly redundant (in a kinematic sense), i.e., there are many potential ways to coordinate body movements to initially succeed at the task (Yamamoto and Tsutsui, 2021), and performance is dependent on the tempo selected (Yamamoto et al., 2018). In addition, they respond to different performance and practice conditions in varying ways (Anderson et al., 2021). Motor learning, performance and transfer are highly specific and individualized (Pacheco et al., 2019). Considerable individual differences exist even at the level of basic reaction time and all the more so for complex coordination (Anderson et al., 2021). In addition, variability in growth patterns and movement experiences likely contribute to the observed variation in initial performance levels (King et al., 2012). Thus, it seems that participants with a background in an upper-limb-involved sport like tennis or basketball may have started with a better initial performance level.

As discussed before, three balls cascade juggling is a complex motor skill that requires simultaneous control of multiple movements and a high level of bimanual eye-hand coordination (Berchicci et al., 2017). Perception and anticipation of the moving balls determines the planning of subsequent motor actions (Draganski and May, 2008). In some ways, juggling is an all or nothing task, due to the high level of motor abilities required for scoring one point. As observed in the results, many participants did not even reach a single point, even after completing all of the training.

4.1. Limitations

While our research exhibited some insightful findings, it is important to acknowledge and address certain limitations that might influence the results. One key limitation is the duration of our study. In this study, participants arrived for 1 hour and accumulated a total practice time (practice and tests together) of 37.5 min. The relatively short time frame allocated for the experiment might have restricted the ability to fully capture the progressive evolution of juggling proficiency within both groups, as mastery of three ball cascade juggling typically takes significantly longer - acquisition of the three-ball cascade requires three learning processes: the cognitive stage (where large demands are placed on the learner to understand the instructions and formulate strategies), the associative phase (involving proceduralizing of task strategies to enhance performance and reduce errors), and the autonomous phase (when the task becomes automatic) (Bebko et al., 2003). In another study (Morita et al., 2016), participants practiced juggling for 15 min and then underwent a total of 45 min of tests conducted at three different time points. The study concluded that participants could not fully master the juggling skill within the limited initial training and practice sessions. In other words, most subjects remained in the learning stages of juggling. Another factor that should be considered is the relatively small sample size ($N = 40$, 20 per group). A larger participant group could have potentially demonstrated clearer results with less statistical error and less effects of individual differences.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://doi.org/10.6084/m9.figshare.24018024.

Ethics statement

The studies involving humans were approved by the Tel Aviv University Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

NG: Conceptualization, Investigation, Project administration, Writing – original draft, Writing – review & editing. AM: Conceptualization, Funding acquisition, Writing – review & editing. JF: Conceptualization, Formal analysis, Funding acquisition, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. Funding was provided by the German Israeli Foundation for Scientific Research & Development (GIF), grant number I-1503-409.10/2019.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1284053/full#supplementary-material

References

Anderson, D. I., Lohse, K. R., Lopes, T. C. V., and Williams, A. M. (2021). Individual differences in motor skill learning: past, present and future. *Hum. Mov. Sci.* 78:102818. doi: 10.1016/j.humov.2021.102818

Bebko, J. M., Demark, J. L., Osborn, P. A., Majumder, S., Ricciuti, C. J., and Rhee, T. (2003). Acquisition and automatization of a complex task: an examination of three-ball Cascade juggling. *J. Mot. Behav.* 35, 109–118. doi: 10.1080/00222890309602126

Berchicci, M., Quinzi, F., Dainese, A., and Di Russo, F. (2017). Time-source of neural plasticity in complex bimanual coordinative tasks: juggling. *Behav. Brain Res.* 328, 87–94. doi: 10.1016/j.bbr.2017.04.011

Brunner, E., Dette, H., and Munk, A. (1997). Box-type approximations in nonparametric factorial designs. *J. Am. Stat. Assoc.* 92, 1494–1502. doi: 10.2307/2965420

Chan, J. S. Y., Luo, Y., Yan, J. H., Cai, L., and Peng, K. (2015). Children's age modulates the effect of part and whole practice in motor learning. *Hum. Mov. Sci.* 42, 261–272. doi: 10.1016/j.humov.2015.06.002

Daumiller, M., Rinas, R., and Jaitner, D. (2021). The relevance of stability and change of achievement goals for self-regulated motor learning processes and outcomes. *Sport Exerc. Perform. Psychol.* 10, 519–535. doi: 10.1037/spy0000260

Draganski, B., and May, A. (2008). Training-induced structural changes in the adult human brain. *Behav. Brain Res.* 192, 137–142. doi: 10.1016/j.bbr.2008.02.015

Gentile, A. M. (1990). "Skill acquisition: action, movement, and Neuromotor processes" in *Movement science: foundations for physical therapy in rehabilitation* (Rockville, MD: Aspen Publishers), 111–187.

Glenn, T. (2019). *Learn to JUGGLE 3 BALLS - beginner tutorial*. Available at: https://www.youtube.com/watch?v=dCYDZDlcO6g (Accessed August 23, 2023).

King, A. C., Ranganathan, R., and Newell, K. M. (2012). Individual differences in the exploration of a redundant space-time motor task. *Neurosci. Lett.* 529, 144–149. doi: 10.1016/j.neulet.2012.08.014

Knapp, C. G., and Dixon, W. R. (1952). Learning to juggle: II. A study of whole and part methods. *Res. Q.* 23, 398–401.

Marmolejo-Ramos, F., Elosúa, M. R., Yamada, Y., Hamm, N. F., and Noguchi, K. (2013). Appraisal of space words and allocation of emotion words in bodily space. *PLoS One* 8:e81688. doi: 10.1371/journal.pone.0081688

Morita, Y., Ogawa, K., and Uchida, S. (2016). Napping after complex motor learning enhances juggling performance. *Sleep Sci* 9, 112–116. doi: 10.1016/j.slsci.2016.04.002

Noguchi, K., Gel, Y. R., Brunner, E., and Konietschke, F. (2012). nparLD: an R software package for the nonparametric analysis of longitudinal data in factorial experiments. *J. Stat. Softw.* 50, 1–23. doi: 10.18637/jss.v050.i12

Pacheco, M. M., Lafe, C. W., and Newell, K. M. (2019). Search strategies in the perceptual-motor workspace and the Acquisition of Coordination, control, and skill. *Front. Psychol.* 10:1874. doi: 10.3389/fpsyg.2019.01874

Palmer, K., Chiviacowsky, S., and Wulf, G. (2016). Enhanced expectancies facilitate golf putting. *Psychol. Sport Exerc.* 22, 229–232. doi: 10.1016/j.psychsport.2015.08.009

Pritchard, J., and Taylor, J. (2022). *The science of alpine ski racing*. (New York: Routeledge).

Qiao, M. (2021). The S-shaped performance curve prevails in practicing juggling. *J. Mot. Learn. Dev.* 9, 230–246. doi: 10.1123/jmld.2020-0048

R Core Team (2023). *R: A language and environment for statistical computing*. (Vienna, Austria: R Foundation for Statistical Computing).

Raviv, L., Lupyan, G., and Green, S. C. (2022). How variability shapes learning and generalization. *Trends Cogn. Sci.* 26, 462–483. doi: 10.1016/j.tics.2022.03.007

Sattelmayer, M., Elsig, S., Hilfiker, R., and Baer, G. (2016). A systematic review and meta-analysis of selected motor learning principles in physiotherapy and medical education. *BMC Med. Educ.* 16:15. doi: 10.1186/s12909-016-0538-z

Sevier, T. L. (2000). The industrial athlete? *Occup. Environ. Med.* 57:285. doi: 10.1136/oem.57.4.285

Shaikh, A., Bhardwaj, S., and Vashista, V. (2023). Learning complex upper-limb movements through practicing movement elements. *Hum. Mov. Sci.* 90:103121. doi: 10.1016/j.humov.2023.103121

Vargha, A., and Delaney, H. D. (2000). A critique and improvement of the CL common language effect size statistics of McGraw and Wong. *J. Educ. Behav. Stat.* 25, 101–132. doi: 10.2307/1165329

Wickens, C. D., Hutchins, S., Carolan, T., and Cumming, J. (2012). Effectiveness of part-task training and increasing-difficulty training strategies. *Hum. Factors* 55, 461–470. doi: 10.1177/0018720812451994

Wulf, G. (2012). "Motor learning" in *Encyclopedia of the sciences of learning*. ed. N. M. Seel (Boston, MA: Springer), 2348–2350.

Yamamoto, K., Shinya, M., and Kudo, K. (2018). Asymmetric adaptability to temporal constraints among coordination patterns differentiated at early stages of learning in juggling. *Front. Psychol.* 9:807. doi: 10.3389/fpsyg.2018.00807

Yamamoto, K., and Tsutsui, S. (2021). Differences in anchoring strategy underlie differences in coordination in novice jugglers. *Acta Psychol.* 215:103273. doi: 10.1016/j.actpsy.2021.103273

Zacks, O., and Friedman, J. (2020). Analogies can speed up the motor learning process. *Sci. Rep.* 10:6932. doi: 10.1038/s41598-020-63999-1

TYPE Original Research
PUBLISHED 15 December 2023
DOI 10.3389/fpsyg.2023.1196978

OPEN ACCESS

EDITED BY
Elizabeth Thomas,
Université de Bourgogne, France

REVIEWED BY
Jaclyn Anne Stephens,
Colorado State University, United States
Phillip Tomporowski,
University of Georgia, United States

*CORRESPONDENCE
Sabine Schaefer
✉ sabine.schaefer@uni-saarland.de

RECEIVED 30 March 2023
ACCEPTED 20 November 2023
PUBLISHED 15 December 2023

CITATION
Monz A, Morbe K, Klein M and Schaefer S (2023) Mutual interference between memory encoding and motor skills: the influence of motor expertise.
Front. Psychol. 14:1196978.
doi: 10.3389/fpsyg.2023.1196978

Mutual interference between memory encoding and motor skills: the influence of motor expertise

Annalena Monz, Kathrin Morbe, Markus Klein and Sabine Schaefer*

Institute of Sport Sciences, Saarland University, Saarbrücken, Germany

In cognitive–motor dual-task situations, the extent of performance decrements is influenced by the attentional requirements of each task. Well-learned motor skills should be automatized, leading to less interference. This study presents two studies combining an episodic memory encoding task with well-practiced motor tasks in athletes. Study 1 asked 40 rowers (early teenagers to middle adulthood) to row on ergometers at slow or fast speeds. In study 2, Taekwondo athletes ($n = 37$) of different skill levels performed a well-practiced sequence of martial arts movements. Performing the motor task during encoding led to pronounced performance reductions in memory in both studies, with costs of up to 80%. Cognitive costs were even larger when rowing with the fast compared to the slow speed in study 1. Both studies also revealed decrements in motor performances under dual-task conditions: Rowing became slower and more irregular (study 1), and the quality of the Taekwondo performance was reduced. Although higher-level athletes outperformed others in motor skills under single-task conditions, proportional dual-task costs were similar across skill levels for most domains. This indicates that even well-practiced motor tasks require cognitive resources.

KEYWORDS

memory encoding, dual-tasking, motor performance, expertise, martial arts, rowing

Introduction

The interplay of cognitive and motor performance is relevant in many everyday situations. For example, people are engaged in a conversation while walking, or they try to remember their grocery shopping list while riding their bicycle. Performing a cognitive and a motor task concurrently often leads to performance decrements (for reviews, see Schaefer, 2014; Koch et al., 2018; Broeker et al., 2022). Classic accounts on the nature of such deficits either propose a limited central resource that has to be shared between the two tasks (Kahneman, 1973), a limited pool of processing resources (Wickens, 2008), or processing stages that can only be operated sequentially by each task (Pashler, 1994).

While most cognitive–motor dual-task studies have been conducted with everyday motor activities such as walking, more challenging motor tasks from a sports context may also be used. In this context, experience with motor skills should enable athletes to reduce their dual-task costs. Theories on motor skill learning predict that automatized tasks require less attention (Fitts and Posner, 1967; Adams, 1971; Gentile, 1972). Dual-process theories propose that human behavior requires two different types of processes. Type 1 processes are independent of attentional control and support the execution of well-learned tasks. Type 2 processes depend on cognitive processing resources, such as attention and working memory capacity (Shiffrin and Schneider, 1977; Kahneman, 2011; Evans and Stanovich, 2013; Furley et al., 2015; Furley and Wood, 2016). They "take over" when the situation is complex and requires higher-order cognitive processes. If intensive experience with a motor skill leads to its automatization, skilled athletes should show smaller dual-task costs than novices when performing a cognitive task concurrently with their motor skills.

For sport-specific task combinations, studies in golf putting, baseball, rugby, soccer, track and field, ice hockey, climbing, or gymnastics reported the predicted performance advantages of experts (Leavitt, 1979; Parker, 1981; Abernethy, 1988; Castiello and Umiltà, 1988; Smith and Chamberlin, 1992; Vuillerme et al., 2001; Beilock et al., 2002a,b, 2004; Gray, 2004; Vuillerme and Nougier, 2004; Gabbett et al., 2011; Green and Helton, 2011; Gabbett and Abernethy, 2013; Darling and Helton, 2014). However, there is considerable variation in study designs concerning the use of discrete actions (e.g., reaction-time tasks and throwing a ball at a target) vs. continuous tasks (e.g., running, maintaining posture, skating, and working memory updating). In addition, many studies instructed participants to maintain their motor task performance under dual-task conditions and used the cognitive task primarily to disturb the execution of the motor task (in the sense of a "secondary task"). Single-task baseline performance in cognition has often not been measured at all. This makes it difficult to get a full picture of dual-task deficits. We argue that performance changes from single- to dual-task conditions should be measured for both task domains (Li et al., 2005; Schaefer, 2014; Plummer and Eskes, 2015). Proportional dual-task costs express the performance decrements in relation to each individual's baseline performance (Somberg and Salthouse, 1982). This allows for a comparison of performance decrements across task domains and groups and can reveal reciprocal dual-task effects (Plummer and Eskes, 2015) and task prioritization strategies (Li et al., 2005).

Taking these considerations into account, a study by Schaefer and Scornaienchi (2019) asked young expert and novice table tennis players to perform a working memory task while returning balls from a ball machine. The cognitive task, 3-back, was a continuous working memory updating task. Participants were presented with a stream of numbers and had to compare the current number to the number presented three positions earlier in the sequence. Stimulus presentations of balls and numbers were varied within subjects by either presenting a ball and a number in the same time window or one after the other, avoiding central or peripheral processing bottlenecks (Abernethy, 1988; Pashler, 1994). There were no differences between experts and novices in their 3-back performances under single-task conditions. However, novices showed higher cognitive dual-task costs. For table tennis (number of balls returned successfully), experts outperformed novices already in the single task. Across both task domains, experts consistently showed costs of about 10%, while novices showed costs between 30% and 50%. However, concurrent vs. alternating stimulus presentation did not influence dual-task costs in this study.

Schaefer and Amico (2022) expanded these findings in another sample of table tennis experts and novices. In addition to 3-back and table tennis returns (timed tasks), each subject also performed the task of counting backward in steps of 7 and table tennis serves (self-initiated tasks). All combinations of cognitive and motor tasks were assessed in a within-subjects design under single- and dual-task conditions. It was assumed that self-initiated tasks should increase dual-task costs since the scheduling of the responses requires attentional resources. As in the previous study, dual-task costs of novices were considerably higher (35%) than those of experts, who did not show costs (−1%). Costs for self-initiated tasks were higher only in the experts, while novices showed a tendency to reduce their dual-task costs for self-initiated tasks. The authors attribute this to the psychometric properties of the underlying tasks since timed tasks were specified by a fixed number of targets and responses.

Another recent set of studies by Amico and Schaefer (2022) used tennis instead of table tennis as the motor task and focused on expert vs. intermediate players instead of novices. For the tennis task, participants had to return balls to a target field. Two different cognitive tasks were used: a 3-back working memory task and a vocabulary-learning task (episodic memory). Dual-tasking led to performance reductions in both cognitive tasks, but the accuracy of tennis returns remained stable under cognitive challenge. Skilled tennis players showed a task-prioritization strategy in favor of the tennis task in the dual-task situation (see also Plummer and Eskes, 2015). Intermediate players showed higher overall dual-task costs than experts in the study with 3-back. However, the group differences in dual-task costs did not reach significance when subjects were asked to learn vocabulary, possibly due to less pronounced expertise differences between the groups.

A recent review by Tomporowski and Qazi (2020) on cognitive–motor interference effects on declarative memory suggests that the type of concurrent motor task and the characteristics of the performer may influence dual-task performance patterns. The authors summarize different theoretical assumptions on the dual-task interplay between physical exercise and cognition. According to arousal theories, the intensity of the exercise will influence whether it exerts facilitative or inhibitory effects on concurrent memory encoding. With low or intermediate intensities, an acute bout of physical exercise can be beneficial for memory performance (Schmidt-Kassow et al., 2010, 2013, 2014; McMorris and Hale, 2012; Roig et al., 2013, 2016; Loprinzi et al., 2019). This may be due to changes in physiological arousal and the release of neurotransmitters and nerve growth factors (see reviews by McMorris, 2016; Loprinzi et al., 2019). However, if the concurrent exercise is too intense, cognitive performance is likely to suffer (see also Dietrich, 2006; Dietrich and Audiffren, 2011).

On the other hand, attention theories would predict that any type of motor task that requires attention should lead to decrements in the concurrent cognitive activity, namely the encoding of the to-be-remembered words. Note that theories on motor skill learning and dual-process theories (Adams, 1971; Gentile, 1972; Shiffrin and Schneider, 1977; Furley et al., 2015) would make similar predictions, with the additional assumption that well-learned tasks require fewer attentional resources.

The current article presents two studies on the influence of motor skill level in cognitive–motor dual-tasking. Study 1 asked rowers in four different ability groups (teenagers to middle-aged adults) to row on ergometers with two different speeds, easy and hard. For rowing, a single generalized motor program is established and performed using online interoceptive and exteroceptive feedback. Rowing speeds were calibrated to each individual's performance level. Study 2 recruited Taekwondo athletes of three different expertise levels. Taekwondo, as a sport, makes use of an elaborate grading system, as reflected by the color of the athlete's belt (black being the highest). The motor task consisted of performing a pre-specified elaborate sequence of martial art movements ("practicing forms"), similar to a dance, with movement quality being rated by expert judges. Forms are sets of prearranged movements to simulate interactions with imaginary opponents (Minarik, 2014, p. 33; Johnson, 2019, p. 1,650).

The cognitive task of both studies is an episodic memory task, the Method-of-Loci. For this task, participants are instructed to use a pre-specified sequence of location cues to encode word lists. The task has been used successfully in several cognitive–motor dual-task studies in different age groups (Kliegl et al., 1990; Li et al., 2001; Schaefer et al., 2008; Amico and Schaefer, 2020, 2022). In the current set of studies, participants perform the cognitive task under single-task conditions while simultaneously rowing on the ergometer (study 1) or performing the martial arts movements (study 2).

The motor and cognitive tasks of the current studies are continuous. While rowing is a cyclic motor skill requiring primarily strength and endurance, performing Taekwondo forms demands timing, movement accuracy, and coordination. Participants are asked to work on the tasks for a prolonged period. Performances and costs are presented on a macro-level, aggregating over several responses (see also Koch et al., 2018, p. 561). The paradigm is, therefore, not suited to answer specific questions about the scheduling of processing steps of each task or about central or peripheral bottlenecks (Pashler, 1994; Hommel, 2020; Huestegge and Strobach, 2021). The studies had not been planned to investigate gender differences since previous dual-task studies often did not find interactions between dual-task costs and gender (Hirsch et al., 2019).

To summarize, study 1 (rowing) investigates whether rowing in two different intensities diminishes memory performance and whether motor expertise moderates this influence. Study 2 assesses whether practicing a form in Taekwondo during memory encoding leads to performance decrements. For both studies, we predict that higher-level athletes are more successful in keeping up their cognitive performances under dual-task conditions. Since single- and dual-task performances are assessed repeatedly for each task involved, we can also investigate whether rowing speed and rowing regularity suffer from dual-tasking (study 1) and whether practicing Taekwondo forms is performed less well under dual-task conditions (study 2). In addition, the calculation of proportional dual-task costs allows for a comparison of findings across groups, tasks, and studies.

Study 1: Rowing

Methods

Participants

Participants were recruited from a local rowing club in Saarbrücken. The club's training groups differed in performance level, with the younger teenagers (teens 1; 5 men, 5 women) being relative beginners, the older teenagers having more experience in rowing (teens 2; 10 men), the young adults belonging to an elite performance group that regularly takes part in competitions at the regional and national levels (young adults; 8 men, 2 women), and the middle-aged adults (4 men, 6 women) being master athletes who do not compete on a regular basis anymore. Table 1 presents the background information for each group. All participants had normal or corrected-to-normal vision and hearing and gave informed consent to the study. The study was approved by the ethics committee of Saarland University.

A statistical power analysis was performed for sample size estimation (GPower 3.1; Faul et al., 2007). Within-subjects designs and highly reliable measures increase statistical power (Brysbaert and Stevens, 2018; Rouder and Haaf, 2018; Zwaan et al., 2018; Brysbaert, 2019). We expected age- and expertise-related influences on dual-task decrements to be large (Leavitt, 1979; Schaefer and Scornaienchi, 2019; Amico and Schaefer, 2022; Schaefer and Amico, 2022). We conducted a power calculation using the G*3 Power software (Faul et al., 2007), with a significance level of 0.05. The power analysis focused on the interaction effect of expertise/age group and single- vs. dual-task performance decrements. We assumed the correlation among repeated measures to be high ($r = 0.65$; see also Schaefer and Scornaienchi, 2019). The analysis indicated that a medium-to-large effect size of $f = 0.3$ for four groups and two measurement occasions (single- vs. dual-tasking) would lead to an actual power of 0.96 with a total sample size of 40 participants.

Procedure

Each participant took part in four group sessions with up to five participants. Before the first session, participants had familiarized themselves with the MoL memory strategy by watching an educational video recorded by the senior author. The video explains how the method works and presents an example trial of six location-word combinations. In session 1, after assessing the demographic information, participants performed one single-task MoL trial while sitting. They also performed a rowing trial in the easy condition for 180 s, without any concurrent task. Session 2 (easy speed) and session 3 (hard speed) assessed the dual-task performances by presenting the MoL task in the second half of the rowing trial. In session 4, one additional MoL single-task trial was administered, and participants also performed an additional rowing trial in the easy condition without any concurrent task.

Apparatus and experimental tasks

Background measure

Perceptual-motor speed was measured with the Digit-Symbol Substitution task (Wechsler, 1981).

Cognitive task: method of loci

The method of loci task (MoL) is a well-established memory strategy to encode word lists (Kliegl et al., 1990; Li et al., 2001; Schaefer et al., 2008; Amico and Schaefer, 2020). To-be-encoded words are concrete objects, and they are encoded by generating a mental image of the object at a specific location. A predefined sequence of 20 location cues was used in the current study. The locations are part of every apartment (e.g., bed, window, table, and chair). The to-be-learned words were taken from Brehmer et al. (2004). They consisted of concrete German nouns that can be easily imagined, such as objects, animals, or professions. In each trial, participants heard lists of 20 location-word combinations presented auditorily with an inter-stimulus interval of 5 s. The instruction was to encode the to-be-learned word by combining it with the respective location cue via

TABLE 1 Background information about the four groups of Study 1 (rowing).

Age group		Teens 1	Teens 2	Young adults	Middle-aged adults	*p*-values for follow-up comparisons
N (men/women)		10 (5/5)	10 (10/0)	10 (8/2)	10 (4/6)	
Age (years)	*M*	12.8	16	20.5	55.5	
	SD	2.5	0.3	0.7	1.7	
	Range	12–14	14–18	17–24	48–63	
Entertainment (none/music/radio)		7/2/1	3/5/2	1/9/0	6/2/2	
Rowing experience (years)	*M*	1.8	3.4	6.8	12.0	Teens 1 vs. Teens 2 $p = 1.000$ Teens 1 vs. Young $p = 0.058$
	SD	0.6	1.1	3.0	4.7	Teens 1 vs. MA $p < 0.001$ Teens 2 vs. Young $p = 0.412$ Teens 2 vs. MA $p < 0.001$ Young vs. MA $p = 0.041$
Weekly rowing (minutes)	*M*	318	395	616	353	Teens 1 vs. Teens 2 $p = 1.000$ Teens 1 vs. Young $p = 0.007$
	SD	126	190	264	151	Teens 1 vs. MA $p = 1.000$ Teens 2 vs. Young $p = 0.081$ Teens 2 vs. MA $p = 1.000$ Young vs. MA $p = 0.023$
Prescribed target time "Easy"	*M*	195	138	131	175	Teens 1 vs. Teens 2 $p < 0.001$ Teens 1 vs. Young $p < 0.001$
	SD	27	16	10	20	Teens 1 vs. MA $p = 0.154$ Teens 2 vs. Young $p = 1.000$ Teens 2 vs. MA $p < 0.001$ Young vs. MA $p < 0.001$
Prescribed target time "Hard"	*M*	167	120	107	145	Teens 1 vs. Teens 2 $p < 0.001$ Teens 1 vs. Young $p < 0.001$
	SD	29	13	7	22	Teens 1 vs. MA $p = 0.107$ Teens 2 vs. Young $p = 1.000$ Teens 2 vs. MA $p = 0.033$ Young vs. MA $p < 0.001$
Digit symbol test (correct items)	*M*	55.20	59.10	62.40	48.50	Teens 1 vs. Teens 2 $p = 1.000$ Teens 1 vs. Young $p = 0.639$ Teens 1 vs. MA $p = 0.793$
	SD	8.13	8.66	12.55	8.92	Teens 2 vs. Young $p = 1.000$ Teens 2 vs. MA $p = 0.119$ Young vs. MA $p = 0.017$

Target times are expressed in "seconds to row 500 m." The prescribed times were calculated based on each athlete's usual performance. "Entertainment" refers to the activities that participants usually do during their rowing training sessions (none = no concurrent activity, listening to music, listening to the radio). Follow-up analyses for significant group main effects are Bonferroni-corrected. "MA" refers to "Middle-Aged Adults."

mental imagery. Participants were encouraged to include object size, sound, touch, emotions, or movement, depending on their personal preferences. For example, when encoding the word "spider" at the location "table," a participant could imagine a huge hairy spider crawling over the table. The current study used "cued" encoding and recall conditions, presenting the location cue with the word during encoding and the list of locations in the correct order for recall. Immediately after the last word was presented, participants wrote down the remembered words at the corresponding location cue on their answer sheets. There was no time limit for recall. The dependent variable for MoL was the sum of correctly remembered words at the correct location.

The encoding for the MoL task was performed while sitting (single-task condition) or rowing (dual-task condition).

Rowing task

Rowing took place on a rowing ergometer (PM5; Concept Two; Morrisville, Vermont, United States). All participants were accustomed to these ergometers because they are regularly used for training purposes in their rowing club, with the instruction to keep up a specific rowing speed for longer time periods.

The display of the ergometer presents the following information: total rowing time, current time to row 500 m, average time to row 500 m for the entire training session, and current rate of strokes. The largest item on the display is the *current time to row 500 m*, and participants are familiar with using this value to calibrate their rowing intensity. Based on the usual performance level of each participant during the previous winter training period and the feedback from the coach, the experimenter individually calculated two rowing intensities for each person: an easy speed and a hard speed. Heart rates for each condition are presented in Supplementary material 1. Table 1 presents the target times for easy and hard rowing. Each rowing trial lasted 180 s, and the main dependent variables for rowing quality were the average time taken to row 500 m and the *SD* of the time taken to row 500 m (rowing regularity). Since rowing performance was recorded for each 10-s segment of the trial, we could also investigate how strongly participants fluctuated in their rowing performance over time by plotting the rowing performances by segment (see Supplementary material 2).

Single- and dual-task setting

In the single-task trials of MoL, participants performed the cognitive task while sitting on the rowing ergometer without any concurrent motor activity. Rowing trials lasted 180 s. Some rowing trials consisted of two parts. In the first half of the trial, no concurrent cognitive stimuli were presented (single-task rowing). In the second half, participants were presented with the location-word combinations (dual-task rowing). They were instructed to keep up their rowing speed while concurrently encoding the location-word pairs. Immediately following the last pair, the rowing trial ended. Participants listed all the words they could remember, at the correct location, on their answer sheets. There was no time limit for recall.

Overview of analysis

The statistical analysis was conducted via IBM SPSS Statistics 25 (IBM Corporation, Armonk, NY, United States). The reliability for MoL and rowing was tested by calculating Cronbach's alpha. Mixed-design ANOVAs with group (4) as a between-subjects factor and condition (single- vs. dual-tasking) as a within-subjects factor were conducted. For rowing, rowing speed (2: easy vs. hard) was included as an additional within-subjects factor. Furthermore, dual-task costs (DTCs) were calculated, expressing performance reductions under dual-task conditions as a percentage of each individual's single-task performance, with the following formula:

$$\text{DTC in\%} = \frac{\left|\text{mean score}\left(\text{single}\right) - \text{mean score}\left(\text{dual}\right)\right|}{\text{mean score}\left(\text{single}\right)} \cdot 100$$

DTCs for each task domain were analyzed with univariate or mixed-design ANOVAs. For all ANOVAs, *F* values and generalized Eta square values (η_G^2) or partial Eta square values (η_p^2) for effect sizes are reported. To interpret statistical significance, the alpha level $\alpha = 0.05$ was used. Significant main effects and interactions were further investigated by follow-up analyses with Bonferroni correction.

All data and analysis code can be made available upon request to the senior author. Data were analyzed using IBM SPSS Statistics 25 (IBM Corporation, Armonk, NY, United States). The study's design and analyses were not pre-registered.

Results

Participant background information

Table 1 shows that the samples differed concerning their average age, the years that they had been rowing [$F(3, 36) = 12.31$, $p < 0.001$, $\eta^2 p = 0.506$], the minutes that they spent rowing each week [$F(3, 36) = 4.97$, $p = 0.005$, $\eta^2 p = 0.239$], and their Digit Symbol Substitution scores [$F(3, 36) = 3.77$, $p = 0.019$, $\eta^2 p = 0.239$]. The Digit Symbol scores corresponded to samples of other representative studies (see Schmiedek et al., 2010), with young adults outperforming middle-aged adults.

Method of loci task

The reliability coefficient based on the four MoL trials was excellent ($\alpha = 0.930$), indicating that the interindividual differences in memory performance remained stable over consecutive trials. Results are presented in Figure 1. Note that performances of the two single-task MoL trials from session 1 and session 4 were averaged to control for practice effects over the course of the study. The mixed-design ANOVA with group (4: teens 1, teens 2, young, and middle-aged) as a between-subjects factor and condition (3: single-task, dual-easy, dual-hard) as a within-subjects factor showed a significant main effect of single- vs. dual-tasking, $F(2, 72) = 171.00$; $p < 0.001$; $\eta_G^2 = 0.466$. MoL performances decreased linearly from single-task to dual-task with easy and hard rowing speeds. The main effect of group also reached significance, $F(3, 36) = 3.34$, $p = 0.004$, $\eta_G^2 = 0.267$, and there was a significant interaction of group and condition, $F(6, 72) = 2.25$, $p = 0.048$, $\eta_G^2 = 0.033$.

To follow-up the significant interaction of group and condition, ANOVAs for each of the three conditions revealed a significant main effect of group for MoL single-task performances, $F(3, 36) = 6.13$, $p = 0.002$, $\eta_p^2 = 0.338$. Bonferroni-corrected comparisons revealed significant differences between older teenagers and middle-aged adults ($p = 0.015$, $M_{Diff} = 4.800$, 95%-CI [0.69, 8.91]), as well as between young and middle-aged adults ($p = 0.002$, $M_{Diff} = 5.900$, 95%-CI [1.79, 10.01]). MoL performances also differed between groups when concurrently rowing with the easy speed, $F(3, 36) = 3.50$, $p = 0.025$, $\eta_p^2 = 0.226$. The only significant difference in the Bonferroni-corrected multiple comparisons was between young and middle-aged adults ($p = 0.028$, $M_{Diff} = 5.10$, 95%-CI [0.38, 9.82]). While rowing with the hard speed, MoL performances again differed significantly across groups, $F(3, 36) = 5.18$, $p = 0.004$, $\eta_p^2 = 0.302$, due to significant differences between young and middle-aged adults ($p = 0.003$, $M_{Diff} = 5.00$, 95%-CI [1.34, 8.66]). Across all analyses, young adults showed the highest MoL scores, and middle-aged adults showed the lowest scores.

Rowing performance: mean time to row 500 m

The reliability coefficient based on the rowing performances in the four segments of the rowing trials (single- and dual-task segments of the easy and hard trials) was excellent ($\alpha = 0.997$).

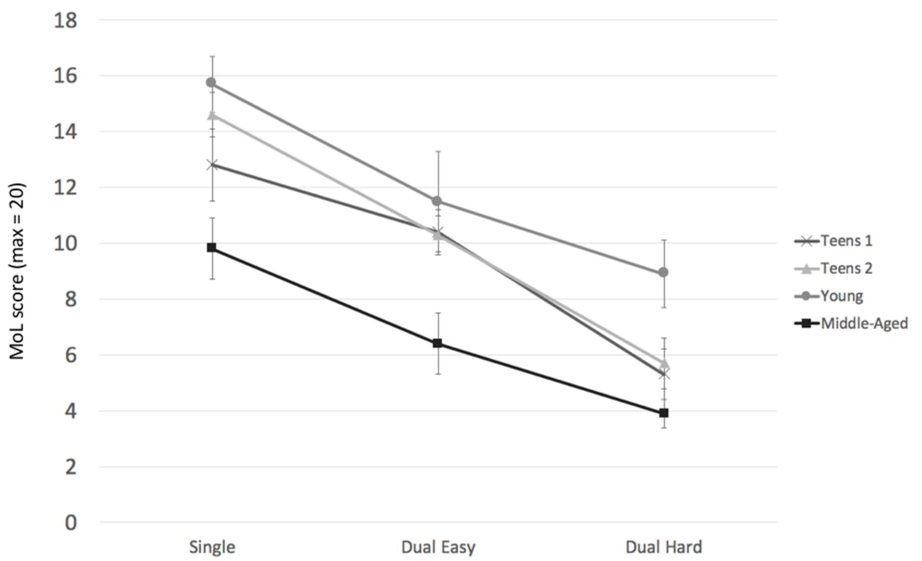


FIGURE 1
Memory performances by single- and dual-task condition and age group, study 1 (Rowing). Participants encoded the word-location pairs while sitting in the "Single" Condition. In the "Dual Easy" condition, participants were rowing at an easy speed while encoding the location-word pairs. The rowing speed was faster in the "Dual Hard" condition. Error bars = SE mean.

To compare the difference in performance from single- to dual-tasking, a mixed-design ANOVA was calculated, with rowing intensity (2: easy vs. hard) and single- vs. dual-tasking (2: first vs. second part of the respective trial) as within-subjects factors and group (4: teens 1, teens 2, young, and middle-aged) as a between-subjects factor. The main effect of rowing intensity reached significance, $F(1, 36) = 177.92$; $p < 0.001$; $\eta_G^2 = 0.272$. Participants rowed faster in the hard rowing intensity. There was no interaction of rowing intensity and group, $F(3, 36) = 2.40$; $p = 0.084$; $\eta_G^2 = 0.015$. There was also a significant main effect of dual-tasking, $F(1, 36) = 217.93$; $p < 0.001$; $\eta_G^2 = 0.106$, due to performance reductions under dual-task conditions. Dual-tasking interacted with group, $F(3, 36) = 5.87$; $p = 0.002$; $\eta_G^2 = 0.010$. While the two-way interaction of rowing intensity and single- vs. dual-tasking failed to reach significance, $F(1, 36) = 1.85$; $p = 0.183$; $\eta_G^2 = 0.001$, there was a significant three-way interaction of rowing intensity, single- vs. dual-tasking, and group, $F(3, 36) = 3.58$; $p = 0.023$; $\eta_G^2 = 0.003$. The main effect of group also reached significance, $F(3, 36) = 28.03$; $p < 0.001$; $\eta_G^2 = 0.677$. Young adults showed the fastest rowing speeds, and the younger teenagers showed the slowest speeds. Figure 2 presents the pattern of findings.

For follow-up analyses, we conducted ANOVAs with rowing intensity (2) and single- vs. dual-tasking (2) for each age group separately. Table 2 presents the results. The main effects of rowing intensity reached significance in each of the four groups, with faster rowing speeds in the "hard" compared to the "easy" condition. In addition, rowing while encoding the MoL words led to a deterioration of rowing performance in each group. However, the interaction of rowing intensity and single- vs. dual-tasking did not reach significance in any of the groups due to the Bonferroni correction of the p-values to $p = 0.0125$.

Rowing performance: SDs of time to row 500 m

To address the fluctuations in rowing speed, we also investigated the standard deviations (*SD*s) of rowing times (per 500 m) for rowing under single- and dual-task conditions. Figure 3 presents the pattern of findings.

A mixed-design ANOVA was calculated, with rowing intensity (2: easy vs. hard) and single- vs. dual-tasking (2: first vs. second segment of the respective trial) as within-subjects factors and group (4: teens 1, teens 2, young, and middle-aged) as a between-subjects factor. The main effect of rowing intensity reached significance, $F(1, 36) = 17.16$; $p = 0.002$; $\eta_G^2 = 0.236$. Rowing was less regular in the easy speed. There was no interaction of rowing intensity and group, $F(3, 36) = 0.40$; $p = 0.756$; $\eta_G^2 = 0.007$. The was also a significant main effect of dual-tasking, $F(1, 36) = 199.38$; $p < 0.001$; $\eta_G^2 = 0.574$, due to increased rowing irregularity under dual-task conditions. Dual-tasking interacted with group, $F(3, 36) = 4.26$; $p = 0.012$; $\eta_G^2 = 0.323$. The two-way interaction of rowing intensity and single- vs. dual-tasking also reached significance, $F(1, 36) = 15.90$; $p < 0.001$; $\eta_G^2 = 0.105$, but there was no significant three-way interaction of rowing intensity, single- vs. dual-tasking, and group, $F(3, 36) = 0.64$; $p = 0.592$; $\eta_G^2 = 0.014$. The main effect of group also reached significance, $F(3, 36) = 16.09$; $p < 0.001$; $\eta_G^2 = 0.269$. Young adults showed the most regular rowing of all groups.

For follow-up analyses, we conducted ANOVAs with rowing intensity (2) and single- vs. dual-tasking (2) for each age group separately. Table 3 presents the results. Due to the Bonferroni correction of the p-values to $p = 0.0125$, the main effects of rowing intensity did not reach significance in any of the four groups. However, rowing while encoding the MoL words led to a significantly less consistent rowing pattern, with more fluctuations in each group. The interaction of rowing intensity and single- vs. dual-tasking only reached significance in older teenagers.

Results for each 10-s segment of a trial are presented in Supplementary material 2. An analysis of the rowing-only trials in the easy condition (assessed in sessions 1 and 4) shows that performance reductions in dual-task rowing were not due to fatigue effects but due to cognitive load (see Supplementary material 2 for details).

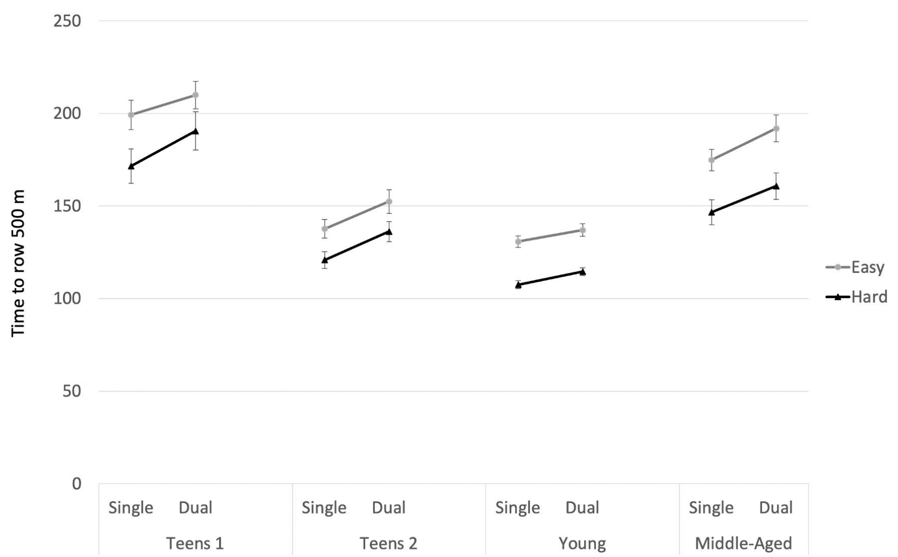


FIGURE 2
Rowing Times by task difficulty, single- vs. dual-task condition, and age group, study 1. Rowing for the "Single" conditions was assessed in the first part of the respective trial when no location-word pairs were presented. The "Dual" condition was assessed in the second half of the trial while encoding the word-location pairs. Error bars = SE mean.

TABLE 2 Results of follow-up analyses for the mixed-design ANOVA on mean times to row 500 m.

Age group	Teenager 1	Teenager 2	Young adults	Middle-aged adults
Main effect rowing intensity	$F(1, 9) = 19.43$	$F(1, 9) = 29.59$	$F(1, 9) = 112.70$	$F(1, 9) = 148.57$
	$p = 0.002$	$p < 0.001$	$p < 0.001$	$p < 0.001$
	$\eta_p^2 = 0.683$	$\eta_p^2 = 0.767$	$\eta_p^2 = 0.926$	$\eta_p^2 = 0.943$
Main effect single vs. dual	$F(1, 9) = 49.19$	$F(1, 9) = 49.20$	$F(1, 9) = 69.78$	$F(1, 9) = 88.18$
	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
	$\eta_p^2 = 0.845$	$\eta_p^2 = 0.845$	$\eta_p^2 = 0.886$	$\eta_p^2 = 0.907$
Interaction intensity × single–dual	$F(1, 9) = 7.58$	$F(1, 9) = 0.08$	$F(1, 9) = 0.13$	$F(1, 9) = 1.47$
	$p = 0.022$	$p = 0.784$	$p = 0.724$	$p = 0.257$
	$\eta_p^2 = 0.457$	$\eta_p^2 = 0.009$	$\eta_p^2 = 0.014$	$\eta_p^2 = 0.140$

Dual-task costs

To compare the differences in performance between the four groups across the single- and dual-task conditions for the motor domain (rowing easy and rowing hard) and the cognitive domain (MoL), percentage scores for the dual-task costs (DTCs) have been calculated.

The left-hand side of Figure 4 illustrates the DTCs for this study. DTCs for MoL are presented in Figure 4A, and DTCs for rowing are presented in Figure 4C.

For the cognitive DTCs, a mixed-design ANOVA with rowing intensity (2: easy vs. hard) as a within-subjects factor and group (4: teens 1, teens 2, young, and middle-aged) as a between-subjects factor was calculated. The main effect of rowing intensity reached significance, $F(1, 36) = 64.37$; $p < 0.001$; $\eta_G^2 = 0.364$. Cognitive costs were higher when rowing at a fast speed. There was also a significant interaction of rowing intensity and group, $F(3, 36) = 3.74$; $p = 0.020$; $\eta_G^2 = 0.091$. The main effect of group did not reach significance, $F(3, 36) = 1.35$; $p = 0.275$; $\eta_G^2 = 0.071$.

Paired sample t-tests were conducted within each age group to follow up on the interaction of rowing intensity and group. Rowing with higher intensity increased the cognitive costs in each age group [teens 1: $t(9) = 5.18$, $p < 0.001$; teens 2: $t(9) = 4.89$, $p < 0.001$; young: $t(9) = 3.19$, $p = 0.005$; middle-aged: $t(9) = 2.72$, $p = 0.012$].

For the DTCs in rowing speed, the mixed-design ANOVA with rowing intensity (2: easy vs. hard) as a within-subjects factor and group (4: teens 1, teens 2, young, and middle-aged) as a between-subjects factor revealed a significant main effect of rowing intensity, $F(1, 36) = 7.93$; $p = 0.008$; $\eta_G^2 = 0.072$. Motor costs were higher when rowing at a fast speed. There was no interaction of rowing intensity and age group, $F(3, 36) = 1.80$; $p = 0.165$; $\eta_G^2 = 0.050$. The main effect of age group reached significance, $F(3, 36) = 4.80$; $p = 0.007$; $\eta_G^2 =$

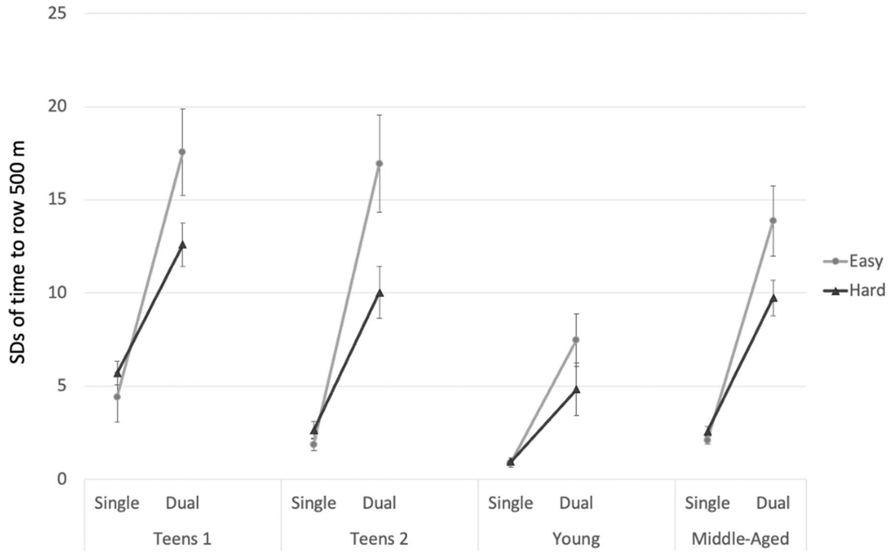


FIGURE 3
SDs of rowing times for Study 1. Error bars = SE mean.

TABLE 3 Results of follow-up analyses for the mixed-design ANOVA on SDs to row 500 m.

Age group	Teenager 1	Teenager 2	Young adults	Middle-aged adults
Main effect rowing intensity	$F(1, 9) = 1.67$	$F(1, 9) = 7.81$	$F(1, 9) = 1.04$	$F(1, 9) = 3.43$
	$p = 0.229$	$p = 0.021$	$p = 0.334$	$p = 0.097$
	$\eta_p^2 = 0.156$	$\eta_p^2 = 0.465$	$\eta_p^2 = 0.104$	$\eta_p^2 = 0.276$
Main effect single vs. dual	$F(1, 9) = 53.42$	$F(1, 9) = 44.47$	$F(1, 9) = 65.30$	$F(1, 9) = 66.66$
	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
	$\eta_p^2 = 0.856$	$\eta_p^2 = 0.832$	$\eta_p^2 = 0.879$	$\eta_p^2 = 0.881$
Interaction intensity × single–dual	$F(1, 9) = 3.13$	$F(1, 9) = 9.98$	$F(1, 9) = 1.19$	$F(1, 9) = 5.49$
	$p = 0.111$	$p = 0.012$	$p = 0.304$	$p = 0.044$
	$\eta_p^2 = 0.258$	$\eta_p^2 = 0.526$	$\eta_p^2 = 0.117$	$\eta_p^2 = 0.379$

0.205. Bonferroni-corrected post-hoc comparisons of the four age groups for their overall rowing DTCs showed that the only comparison reaching significance was between teens 2 and young adults, $p = 0.001$, $M_{Diff} = 5.971$, 95%-CI[1.445, 10.497], with young adults showing the lowest level of motor costs.

Discussion study 1

The findings of study 1 show that rowing on an ergometer while concurrently encoding word lists leads to considerable performance reductions: Participants encode fewer words while rowing, and they also show clear reductions in their rowing speeds, as well as their rowing regularity (see Supplementary material 2). Dual-task costs in both task domains (MoL and rowing) are even more pronounced when rowing with a faster speed. Although there are some interactions with the group factor, differences between groups in these effects tend to be small, and the overall pattern of dual-task performance reductions is consistent across groups.

Our findings contradict accounts that postulate improvements in episodic memory tasks due to an optimization of arousal levels via exercise bouts of low or intermediate intensities (Schmidt-Kassow et al., 2010, 2013, 2014; McMorris and Hale, 2012; Roig et al., 2013, 2016; Loprinzi et al., 2019). Instead, we found a linear decrease in memory performance from single-task to dual-task memory encoding, which is further increased when exercising with higher intensities. These findings are in line with dual-process theories (Shiffrin and Schneider, 1977; Furley et al., 2015). They also support a recent study by Longman et al. (2017), who reported cognitive and physical performance reductions in young rowers performing a rowing ergometer task combined with a free-recall task. In the Longman et al. study, participants had been instructed to produce maximum power output while rowing. This produced

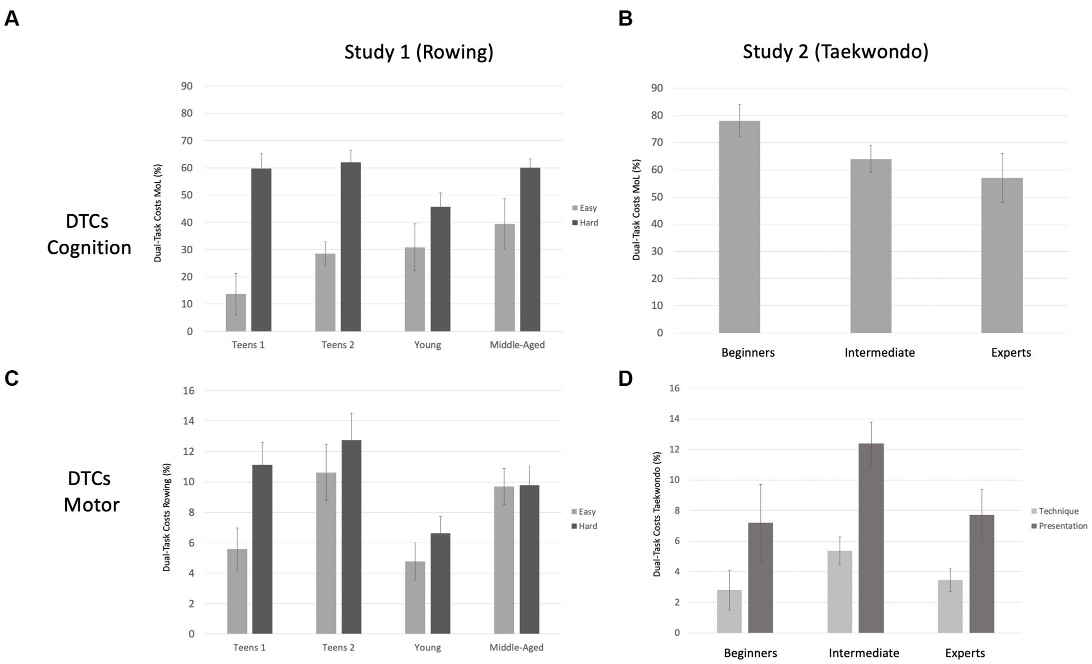


FIGURE 4
Dual-task costs for both studies. The left-hand side of the figure presents the DTCs for study 1 **(A,C)**, and the right-hand side presents the DTCs for study 2 **(B,D)**. Costs in cognition (MoL) are presented in the first row, and costs for motor tasks (rowing in study 1, Taekwondo in study 2) are presented in the second row. Error bars = SE mean.

even higher costs in physical as compared to mental performance. Our findings indicate that rowing on an ergometer with the instruction of keeping up a pre-specified rowing speed is an attention-demanding task.

For study 2, the motor task consisted of a specific sequence of martial arts movements from Taekwondo ("practicing forms"), which is likely to be highly attention-demanding. Participants belonged to different skill groups. We predicted that the need to perform the MoL task concurrently with the Taekwondo movements will elicit cognitive and motor dual-task costs, which should be influenced by the expertise level of the participants.

Study 2: Taekwondo

Methods

Participants

Participants ($N=37$) were recruited from five Taekwondo groups in the Saarland area. Of them, 28 participants practice classic Taekwondo, and the remaining nine participants practice Taekwondo in the World Taekwondo [WT] federation. All participants practiced Taekwondo as an amateur sport and had learned Taekwondo from different instructors. Three participants had experience with participation in Taekwondo form competitions. Considering graduation in Taekwondo, the lowest graduation in the sample is the 8th Kup (yellow belt) and the highest one is the 3rd Dan (black belt).

Participants were separated into three expertise groups based on their graduation in Taekwondo. The 10 participants with a yellow belt (8th and 7th Kup) formed the "relative beginners" group (7 men, 3 women), while the "intermediate level" group consisted of 17 athletes (8 men, 9 women) with a blue and a red belt (6th Kup–1st Kup). The third group ("experts") consisted of 10 athletes (5 men, 5 women) with a black belt. Table 4 presents an overview of the background information of the three groups. All participants provided informed consent to participate in the study. The study was approved by the ethics committee of Saarland University.

A statistical power analysis was performed for sample size estimation (GPower 3.1; Faul et al., 2007). Within-subjects designs and highly reliable measures increase statistical power (Brysbaert and Stevens, 2018; Rouder and Haaf, 2018; Zwaan et al., 2018; Brysbaert, 2019). We expected age- and expertise-related influences on dual-task decrements to be large (Leavitt, 1979; Schaefer and Scornaienchi, 2019; Amico and Schaefer, 2022; Schaefer and Amico, 2022). We conducted a power calculation using the G*3 Power software (Faul et al., 2007), with a significance level of 0.05. The power analysis focused on the interaction effect of expertise/age group and single- vs. dual-task performance decrements. We assumed the correlation among repeated measures to be high ($r=0.65$; see also Schaefer and Scornaienchi, 2019). The analysis indicated that a medium-to-large effect size of $f=0.3$ for four groups and two measurement occasions (single- vs. dual-tasking) would lead to an actual power of 0.96 with a total sample size of 40 participants.

Procedure

The study took place at the Dojang (training site to practice Taekwondo) of the Taekwondo group. Participants initially took part in an instruction session. After the assessment of demographic information and the Digit Symbol test, participants watched an instructional video tutorial on the method of Loci memory strategy,

TABLE 4 Background information about the three groups of Study 2 (Taekwondo).

Demographic variables		Expertise group		
		Beginners (yellow belt)	Intermediate (blue or red belt)	Experts (black belt)
N (men/women)		10 (7/3)	17 (8/9)	10 (5/5)
Age (years)	*M*	39	28	43
	SD	19	15	10
	Range	13–67	13–53	30–63
Experience in Taekwondo (years)	*M*	3.55	7.71	14.30
	SD	1.57	2.71	5.42
Weekly Taekwondo participation (minutes)	*M*	184	142	213
	SD	80	61	112
Digit symbol substitution test (correct items)	*M*	51.90	56	53.10
	SD	9.61	9.82	11.60

followed by two practice trials. For some participants, the instruction session was presented in an online format.

All MoL lists had been recorded in advance, and each list consisted of 15 location-word pairs that were presented with an ISI of 5 s via loudspeaker, resulting in trial lengths of 80 s. Encoding and recall were always cued.

For the testing session, list order was counterbalanced across participants, such that each list appeared equally often under single- and dual-task conditions. The experimenter checked the correctness of the recalled words (maximum score = 15 words). Participants performed the testing session either in casual sportswear or in their typical Taekwondo suit called *Dobok*.

At the beginning of the testing, participants were given 5 min to warm-up and were asked to perform the third form twice for practice. Table 5 presents the order of trials.

In the single-task trials of MoL, participants performed the cognitive task while sitting without any concurrent activity. During the motor single-task trials, participants were filmed while performing the third form of Taekwondo. For the dual-task trials, participants performed the form while concurrently encoding the words. At the end of the recording, a signal was given by the experimenter, and participants had to stop their run immediately. They were asked to recall the presented words in the correct order. For dual-task trials, participants were instructed to focus on both the cognitive and the motor tasks as much as possible.

Following the testing sessions, the videos of the motor task were edited, anonymized, and then sent to the raters. There were no data exclusions, except for one trial of Taekwondo single-task for one participant, which had to be repeated due to technical difficulties. All data and analysis code can be made available upon request to the senior author. Data were analyzed using IBM SPSS Statistics 25 (IBM Corporation, Armonk, NY, United States). The study's design and analyses were not pre-registered.

Apparatus and experimental task

Cognitive task—method of loci

In the cognitive task, participants were asked to encode and repeat words of a given list, similar to study 1. However, in the current study, there were only 15 words per list (instead of 20). The inter-stimulus interval was 5,000 ms.

TABLE 5 Order of trials in study 2.

1	Cognitive single-task (MoL)
2	Motor single-task (3rd form of Taekwondo)
3	Dual-task trial 1
4	Dual-task trial 2
5	Motor single-task (3rd form of Taekwondo)
6	Cognitive single-task (MoL)

Motor task—3rd form in Taekwondo

The motor task was the performance of the third Taekwondo form. A form of Taekwondo is a systematic, prearranged sequence of martial techniques used against one or more imaginary opponents (Minarik, 2014, p. 33). Participants perform a pre-specified sequence of stances, hand attacks, blocks, and kicks, which are to be presented with high precision. We chose the third form, named *To-San-Hyong* or *Taeguk sam jang,* because its difficulty level is optimal for the current study.

Participants were instructed to perform the form twice in a row. This specification was made for two reasons: First, the duration of the performance of the third form usually takes about 30 s. The recording of the MoL word lists takes about 80 s. To ensure that participants were moving until the recording was over, they were instructed to restart and repeat the form until the last pair of words had been presented. We expected that during the given 80 s, two complete runs of the form are possible. Participants were filmed while performing the form. All videos were edited so that the number of runs per video was equal under single- and dual-task conditions (2 runs each). There was only one exception for one slow participant who performed only one form under dual-task conditions.

The videos were rated independently by two raters, who were experienced scoring judges of official Taekwondo competitions. The raters are holders of the 3rd and the 4th Dan in Taekwondo and have been practicing Taekwondo for more than 30 years. Raters were not aware whether a specific form had been performed under single- or dual-task conditions. The rating was done using the *Jury's Paper* of the DTU (2019), based on the following categories: *technique* and *presentation*. The domain *technique* refers to the accuracy of the martial techniques shown by the athlete, whereas *presentation* is measured by velocity and force, rhythm, and the expression of energy during the performance. The score on the *Jury's paper* had been modified by doubling the possible points in each category. For two runs, the possible total score therefore was between 3 and 20 points, consisting of 0 to 8 points for *technique* and 3 to 12 points for *presentation*. For the one participant with only one valid run, the score was doubled.

Overview of analysis

The statistical analysis was performed via IBM SPSS Statistics 28 (IBM Corporation, Armonk, NY, United States).

We report ANOVAs on some background variables at the beginning of the Results section. The scores for the two trials in each domain (Taekwondo form: score in technique and score in presentation; score in MoL) were averaged across the respective conditions (single and dual).

The reliability of each of the three domains was tested by calculating Cronbach's alpha. Mixed-design ANOVAs with expertise (3) as a between-subjects factor and condition (2: single- vs. dual-tasking) as a within-subjects factor were conducted for each of these dependent variables. In addition, dual-task costs were calculated. For MoL, a univariate ANOVA was conducted to reveal group differences in cognitive costs. For DTCs in Taekwondo, mixed-design ANOVAs with expertise (3) as a between-subjects factor and an evaluation category (2: technique, presentation) were conducted.

In addition, analyses for trial durations and the inter-rater reliabilities for the Taekwondo judges are reported in Supplementary materials 3, 4.

Results

Participant background information

A one-way ANOVA with group (3) revealed a significant effect of group for the average age, $F(2, 34) = 3.78$, $p = 0.033$, $\eta_p^2 = 0.182$. The Bonferroni-corrected follow-up tests showed a significant difference only between intermediate-level athletes and experts ($p = 0.045$, $M\_Diff = 15.276$, 95%-CI [0.26, 30.30]). There was no significant difference between the groups regarding their average weekly Taekwondo participation, $F(2, 34) = 0.196$, $p = 0.823$, $\eta_p^2 = 0.011$. Not surprisingly, there were significant differences between the groups regarding their mean experience in Taekwondo, $F(2, 34) = 24.90$, $p < 0.001$, $\eta_p^2 = 0.594$. The Bonferroni-corrected follow-up tests revealed significant differences between all three groups (beginners and experts: $p < 0.001$, $M\_Diff = 10.75$, 95%-CI[6.87, 14.63]; intermediates and experts: $p < 0.001$, $M\_Diff = 6.594$, 95%-CI[3.135, 10.053]; beginners and intermediates: $p = 0.014$, $M\_Diff = 4.156$, 95%-CI[0.697, 7.615]). There were no differences between the groups in their cognitive speed, $F(2, 34) = 0.568$, $p = 0.572$, $\eta_p^2 = 0.032$, as measured with the Digit-Symbol Substitution test (Wechsler, 1981).

Cognitive task–MoL

Cronbach's alpha for the four trials of MoL was high, $\alpha = 0.86$. The mixed-design ANOVA with expertise (3) as a between-subjects factor and single- vs. dual-tasking (2) as a within-subjects factor showed a significant main effect of single- versus dual-tasking, $F(1, 34) = 216.41$; $p < 0.001$; $\eta_G^2 = 0.545$. Participants recalled fewer words under dual-task conditions. The main effect of expertise also reached significance, $F(2, 34) = 3.59$, $p = 0.039$, $\eta_G^2 = 0.146$. However, there was no significant interaction between expertise and single- vs. dual-tasking, $F(2, 34) = 1.25$, $p = 0.300$, $\eta_G^2 = 0.013$. A Bonferroni-corrected *post hoc* analysis revealed no significant differences in the means of the score in MoL between the three expert groups (beginners and experts: $p = 0.055$; experts and intermediate: $p = 1.000$; 2 and 1: $p = 0.097$), but the difference between beginners and experts showed a trend in favor of the experts. The pattern of findings is depicted in Figure 5.

Motor task–3rd form in Taekwondo

The results concerning the Taekwondo form are the average of the ratings of both raters. Cronbach's alpha for the four trials was high for both domains: $\alpha = 0.91$ (technique) and $\alpha = 0.97$ (presentation).

Technique

The findings in the category *technique* are shown in Figure 6. The ANOVA with expertise (3) as a between-subjects factor and single- vs. dual-tasking (2) as a within-subjects factor showed a significant main effect of single- vs. dual-tasking, $F(1, 34) = 46.86$; $p < 0.001$; $\eta_G^2 = 0.058$. The technique was better in the single-task condition. The main effect of expertise also reached significance, $F(2, 34) = 12.39$, $p < 0.001$, $\eta_G^2 = 0.412$. However, there was no significant interaction between expertise and single- vs. dual-tasking, $F(2, 34) = 1.51$, $p = 0.236$, $\eta_G^2 = 0.038$. A Bonferroni-corrected post-hoc analysis revealed a significant difference in the means of the score in *technique* between beginners and experts ($p = 0.001$, $M_{Diff} = 0.80$, 95%-CI[0.28, 1.33]), as well as between intermediates and experts ($p < 0.001$, $M_{Diff} = 0.89$, 95%-CI[0.42, 1.35]), but no significant difference between beginners and intermediates ($p = 1.000$). As expected, experts (holders of a black belt) gained significantly higher scores in *technique* than the other two groups.

Presentation

Figure 7 presents the findings for presentation. For presentation, the ANOVA with expertise (3) as a between-subjects factor and condition (2) as a within-subjects factor showed a significant main effect of single- vs. dual-tasking, $F(1, 34) = 63.91$; $p < 0.001$; $\eta_G^2 = 0.076$. Presentation suffered under dual-task conditions. The main effect of expertise also reached significance, $F(2, 34) = 8.84$, $p < 0.001$, $\eta_G^2 = 0.333$. Yet, there was no significant interaction of expertise and condition, $F(2, 34) = 1.91$, $p = 0.164$, $\eta_G^2 = 0.005$. A Bonferroni-corrected post-hoc analysis revealed a significant difference in the means of the score in *presentation* between beginners and experts ($p = 0.002$, $M_{Diff} = 1.70$, 95%-CI[0.56, 2.83]), as well as between intermediates and experts ($p = 0.003$, $M_{Diff} = 1.50$, 95%-CI[0.46, 2.48]), but no significant difference between beginners and intermediates ($p = 1.000$). Corresponding to expectations, experts (black belts) achieved significantly higher scores in presentation than the other groups.

Dual-task costs

Dual-task costs for each performance domain were calculated based on the formula presented in study 1. The right-hand side of Figure 4 presents the DTCs for MoL (Figure 4B) and for the two Taekwondo dimensions, technique and presentation (Figure 4D).

Expertise groups did not differ significantly in their cognitive DTCs, $F(2, 34) = 2.39$, $p = 0.107$, $\eta_p^2 = 0.123$.

10.3389/fpsyg.2023.1196978

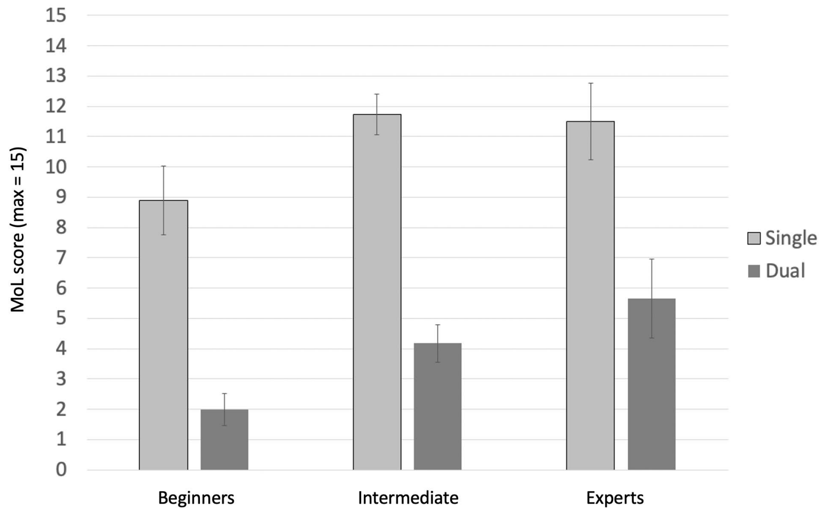


FIGURE 5
Memory performances by single- and dual-task condition and group, Study 2 (Taekwondo). For the single task, memory encoding took place while sitting. For the dual task, participants performed the third form of Taekwondo during encoding. Error bars = SE mean.

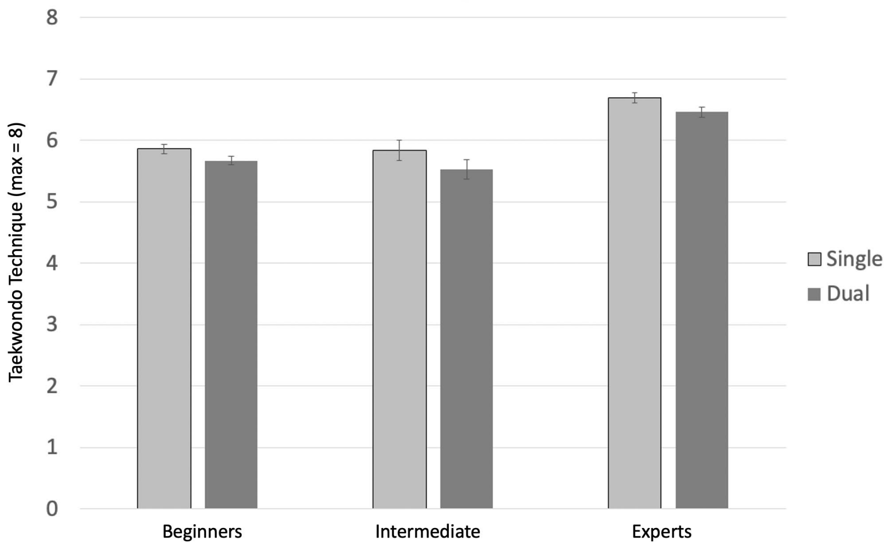


FIGURE 6
Mean scores in Taekwondo technique by single- and dual-task condition and group. Error bars = SE mean.

To examine the difference in the average costs in the Taekwondo domains, a mixed-design ANOVA was calculated, with expertise (3) as a between-subjects factor and an evaluation category (2: technique, presentation) as a within-subjects factor. The analysis revealed a significant main effect of category, $F(1, 34) = 60.72$, $p < 0.001$, $\eta_G^2 = 0.212$. The costs of *presentation* were significantly higher than those of *technique*. The main effect of expertise did not reach significance, $F(2, 34) = 2.7$, $p = 0.082$, $\eta_G^2 = 0.119$. In addition, there was no significant interaction of expertise and category, $F(2, 34) = 2.21$, $p = 0.125$, $\eta_G^2 = 0.019$.

Supplementary material 5 reports scatterplots for the cognitive and motor DTCs for both studies.

Discussion study 2

The findings of study 2 show that doing a form in Taekwondo requires a lot of attention: Participants in each skill level show considerable performance reductions in the concurrent memory task, with reductions between almost 60% in the most advanced

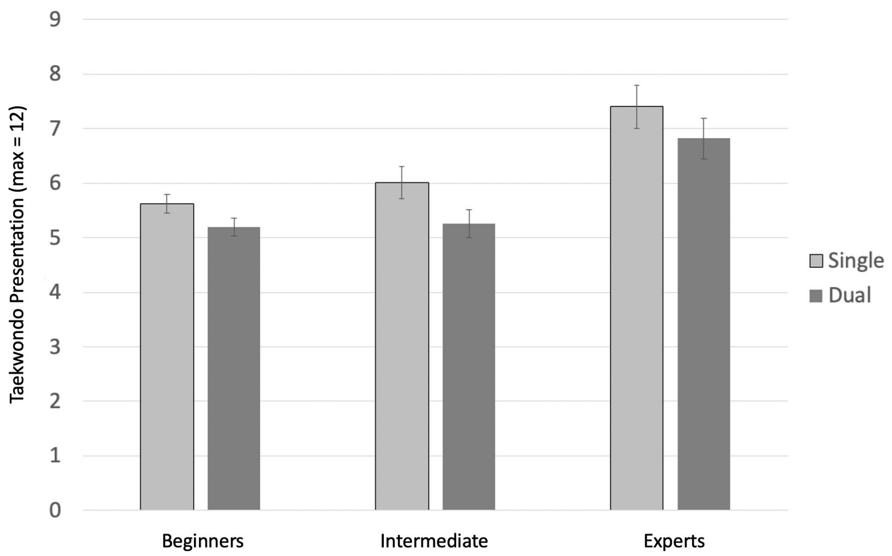


FIGURE 7
Mean scores in Taekwondo presentation by single- and dual-task condition and group. The figure depicts the average score in presentation achieved by each expert group depending on the respective condition (single and dual). Error bars = SE mean.

athletes (black belt) and about 80% in the relative beginners (yellow belt). The quality of the movement is also reduced, as shown by the costs in technique and presentation. The fact that expertise groups did not differ systematically in the extent of the performance decrements may be related to power issues since the study only tested 37 athletes. Consistent with expectations, holders of black belts showed significantly better absolute performances in Taekwondo than the other two groups. Nevertheless, based on the current dataset, even being the holder of a black belt did not protect the athletes from failing to maintain their cognitive and motor performances under dual-task conditions (see also Supplementary material 5).

Study 2 also revealed that motor dual-task costs were higher in the performance category *presentation* than in *technique*, irrespective of graduation. This indicates that encoding words using a mental imagery technique still enables participants to perform the movements in the correct order (*technique*), but movement velocity and force, rhythm, and expression of energy during the performance (*presentation*) suffer more strongly.

General discussion

We investigated whether performing a skilled motor task like rowing on an ergometer (study 1) or presenting a pre-specified sequence of martial arts movements (study 2) results in performance reductions in a concurrent episodic memory task (MoL) and whether dual-task costs are moderated by motor expertise. Subjects in both studies had at least some experience with the respective motor skills, and some were relatively advanced (i.e., the young adult rowers in study 1 and the holders of the black belts in study 2). Nevertheless, performance in both the cognitive and the motor tasks decreased significantly in all groups, indicating that the attentional demands of well-practiced motor skills are considerable.

Previous studies had used MoL memory encoding in combination with different motor tasks (while walking on easy and complex narrow tracks with and without obstacles: Li et al., 2000, 2001; while balancing on an ankle-disc board: Schaefer et al., 2008; while rotating a fidget spinner, doodling, or tracing: Amico and Schaefer, 2020; while doing fast or slow squats: Amico et al., 2023). Participants were children, young, or older adults. Performing a motor task concurrently reduced MoL performances in most studies, with the only exceptions being while kneading a stress ball (Amico and Schaefer, 2020) or while walking on a simple track without obstacles (Li et al., 2000, 2001), both in young adults only.

The highest MoL costs in previous studies occurred when encoding took place while tracing symbols (about 40% in young adults; Amico and Schaefer, 2020), while walking on complex tracks with obstacles (about 40% in older adults; Li et al., 2000, 2001), or while doing squats with every second word (about 35% in young adults; Amico et al., 2023). The cognitive costs of the current studies are considerably higher than that, with about 60% during fast rowing in study 1 and almost 80% for the relatively less-experienced holders of yellow belts in study 2 (see Figure 4). This indicates that the motor tasks of fast ergometer rowing and doing forms in Taekwondo require substantial cognitive processing resources, such as attention and working memory capacity (Shiffrin and Schneider, 1977; Kahneman, 2011; Evans and Stanovich, 2013; Furley et al., 2015).

It may seem somewhat surprising that ergometer rowing reduced cognitive performances considerably since bouts of low- or intermediate-intensity exercise even exerted beneficial effects on memory performance in previous studies (e.g., Schmidt-Kassow et al., 2010, 2013, 2014; see also Loprinzi et al., 2019, for a review). However, concurrent motor tasks were self-paced in these contexts and were not framed as a secondary task. For the current study, participants had been instructed to keep up their predetermined rowing speeds, which requires closely and continuously monitoring the ergometers' display. It would be interesting to disentangle the cognitive requirements of monitoring the ergometer display from the effects of rowing as a motor activity. Therefore, future studies should include a condition in which participants do not receive any online feedback about their rowing speed during the trial but are still instructed to keep up their rowing speed under dual-task conditions. In addition, memory recall in our study took place immediately after the end of the encoding phase. The studies finding positive effects of exercise on memory encoding often assessed memory recall 1 or 2 days later (Schmidt-Kassow et al., 2013, 2014). In the dual-task trials of our study, we cannot rule out that physical fatigue from intense rowing may have led to additional decrements in recall performance. Future research should, therefore, systematically vary the time delay between encoding and recall.

Both studies also found decrements in motor performances caused by the cognitive task: Rowing became slower and more irregular in study 1, and the quality of the Taekwondo presentation suffered. Motor costs were not as high as in cognition (see Figure 4), which may be due to motor tasks being prioritized by the athletes (Gibson, 1979; Schaefer, 2014; Plummer and Eskes, 2015; Amico and Schaefer, 2022). Differential-emphasis instruction can shed further light on the interindividual differences in the ability to shift one's focus of attention strategically (Kramer et al., 1995; Li et al., 2005). In addition, providing participants with more practice in the dual-task situation may reduce their cognitive–motor dual-task costs (Schumacher et al., 2001). However, since every participant of the current study showed costs in at least one of the two tasks (for details, see Supplementary material 5), it is an open question whether extended practice would eliminate their dual-task costs entirely.

From an applied perspective, it is interesting that a skill like rowing seems not to be fully automatized, even in elite rowers. Rowing times in the hard conditions were reduced considerably under dual-task conditions (see Figure 2). In addition, the increase in rowing irregularity is very strong in the current study (see Figure 3), even in the group with the highest performance level. Rowers often perform in groups, which implies that they need to keep their balance on the boat, while at the same time coordinating their rowing with several other athletes. Each of these aspects may require cognitive resources. Therefore, the cognitive demands of the sport are likely to be higher than expected. The fact that only a few of the athletes use entertainment, such as listening to music while training, also hints in this direction (see Table 1). Future research should address each of these aspects separately with systematic experimental manipulations. In addition, neuropsychological measures can add to our understanding of dual-task interference (Leone et al., 2017; Mac-Auliffe et al., 2021).

Limitations and future directions

Both studies would have profited from larger sample sizes. For the cognitive DTCs of study 2, there is a trend in favor of smaller costs for expert athletes. Larger samples should allow for a clearer picture on expertise differences in cognitive–motor dual-tasking. In addition, study 1 should have included a 180-s single-task rowing trial for the hard speed as well to further support the claim that changes in rowing speed under dual-task conditions are not due to physical fatigue.

Motor expertise is not the only factor that can influence cognitive–motor performance trade-offs. There is a rich literature documenting aging-related changes to perform cognitive and motor tasks concurrently, mainly in the context of everyday locomotor activities such as walking or balancing (for reviews, see Beurskens and Bock, 2012; Li et al., 2018; Wollesen and Voelcker-Rehage, 2019; Kahya et al., 2020). To the best of our knowledge, there are few studies that have recruited skilled athletes of advanced age. Study 1 included rowers in middle adulthood, who showed similar performance decrements as the other groups. Findings in even older adults would be very informative. Future research should investigate whether motor expertise may even counteract aging-related decrements (see also Krampe et al., 2014), allowing older individuals to keep up their cognitive and motor performance in challenging dual-task situations.

Future studies should also disentangle different aspects of the motor skill (e.g., motor planning vs. motor execution) and their mutual interference with cognitive tasks (Logan and Fischman, 2011, 2015; Spiegel et al., 2013), which requires a more fine-grained analysis of the temporal dynamics during dual-tasking. As Koch et al. (2018) pointed out, continuous tasks and aggregated performance measures demonstrate dual-task interference on a "macrolevel," making it difficult to reveal task-scheduling and switching processes on a "microlevel." When performing a Taekwondo form, athletes probably rely on the chunking of movements that are called upon and then executed in response to specific attacks (either imagined or real). If the presentation of words for the MoL task coincides with the preparation of specific movement chunks, mutual interference may be higher than during the execution of the movement. Future research should address these temporal dynamics.

Conclusion

The current set of studies combined an episodic memory task with the performance of a continuous, cyclic motor skill requiring primarily strength and endurance (rowing, study 1) or an elaborate motor skill with high demands on timing, movement accuracy, and coordination (Taekwondo forms, study 2). Both studies compared athletes from different ability groups in the extent to which both cognitive and motor performances suffered from the concurrent task. Although higher-level athletes outperformed others in motor skills under single-task conditions, proportional dual-task costs were similar across skill levels. Costs occurred in each individual and in the motor as well as the cognitive domain. This indicates that even well-practiced motor tasks require cognitive resources.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Ethics Committee of Saarland University. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

KM and SS contributed to the conception and design of study 1 (rowing) and performed the statistical analysis for study 1. AM, MK, and SS contributed to the conception and design of study 2 (Taekwondo) and performed the statistical analysis for study 2. MK was involved in the analyses for Supplementary material 4. SS wrote the first draft of the manuscript. AM wrote sections of the manuscript (study 2). All authors contributed to the article and approved the submitted version.

Funding

The research was funded by Saarland University.

Acknowledgments

The authors would like to thank all participants for taking part in the study and Christian Kaczmarek and Kai Leisge for helpful discussions.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1196978/full#supplementary-material

References

Abernethy, A. B. (1988). The effects of age and expertise upon perceptual skill development in a racquet sport. *Res. Q. Exerc. Sport* 59, 210–221. doi: 10.1080/02701367.1988.10605506

Adams, J. (1971). A closed-loop theory of motor learning. *J. Mot. Behav.* 3, 111–149. doi: 10.1080/00222895.1971.10734898

Amico, G., Braun, T., and Schaefer, S. (2023). Can acute resistance exercise facilitate episodic memory encoding? *Curr. Psychol.* 42, 10910–10923. doi: 10.1007/s12144-021-02352-9

Amico, G., and Schaefer, S. (2020). No evidence for performance improvements in episodic memory due to fidgeting, doodling or a "neuro-enhancing" drink. *J Cogn Enhance* 4, 2–11. doi: 10.1007/s41465-019-00124-9

Amico, G., and Schaefer, S. (2022). Tennis expertise reduces costs in cognition but not in motor skills in a cognitive-motor dual-task situation. *Acta Psychol.* 223:103503. doi: 10.1016/j.actpsy.2022.103503

Beilock, S. L., Bertenthal, B. I., Mccoy, A. M., and Carr, T. H. (2004). Haste does not always make waste: expertise, direction of attention, and speed versus accuracy in performing sensorimotor skills. *Psychon. Bull. Rev.* 11, 373–379. doi: 10.3758/BF03196585

Beilock, S. L., Carr, T. H., Macmahon, C., and Starkes, J. L. (2002a). When paying attention becomes counterproductive: impact of divided versus skill-focused attention on novice and experienced performance of sensorimotor skills. *J. Exp. Psychol. Appl.* 8, 6–16. doi: 10.1037//1076-898x.8.1.6

Beilock, S. L., Wierenga, S. A., and Carr, T. H. (2002b). Expertise, attention, and memory in sensorimotor skill execution: impact of novel task constraints on dual-task performance and episodic memory. *Q. J. Exp. Psychol.* 55, 1211–1240. doi: 10.1080/02724980244000170

Beurskens, R., and Bock, O. (2012). Age-related deficits of dual-task walking: a review. *Neural Plast.* 2012:131608. doi: 10.1155/2012/131608

Brehmer, Y., Stoll, G., Bergner, S., Benoit, R., Von Oertzen, T., and Lindenberger, U. (2004). Selection of unambiguous visual words appropriate for children in age-comparable memory experiments: Results of a pilot study. Available at: http://psydok.sulb.uni-saarland.de/volltexte/2004/189/.

Broeker, L., Brüning, J., Fandakova, Y., Khosravani, N., Kiesel, A., Kubik, V., et al. (2022). Individual differences fill the uncharted intersections between cognitive structure, flexibility, and plasticity in multitasking. *Psychol. Rev.* 129, 1486–1494. doi: 10.1037/rev0000376

Brysbaert, M. (2019). How many participants do we have to include in properly powered experiments? A tutorial of power analysis with reference tables. *J. Cogn.* 2, 1–38. doi: 10.5334/joc.72

Brysbaert, M., and Stevens, M. (2018). Power analysis and effect size in mixed effects models: a tutorial. *J. Cogn.* 1, 1–20. doi: 10.5334/joc.10

Castiello, U., and Umiltà, C. (1988). Temporal dimensions of mental effort in different sports. *Int. J. Sport Psychol.* 19, 199–210.

Darling, K. A., and Helton, W. S. (2014). Dual-task interference between climbing and a simulated communication task. *Exp. Brain Res.* 232, 1367–1377. doi: 10.1007/s00221-014-3855-7

DTU. (2019). *Wettkampfordnung Poomsae (Wop).* Available at: https://www.dtu.de/fileadmin/Downloads/Dokumentejan2021/9.1_Wettkampfordnung_Poomsae_Stand_15.09.19.pdf

Dietrich, A. (2006). Transient hypofrontality as a mechanism for the psychological effects of exercise. *Psychiatry Research* 145, 79–83. doi: 10.1016/j.psychres.2005.07.033

Dietrich, A., and Audiffren, M. (2011). The reticular-activating hypofrontaliy (RAH) model of acute exercise. *Neuroscience and Biobehavioral Reviews* 35, 1305–1325. doi: 10.1016/j.neurobiorev.2011.02.001

Evans, J. S. B. T., and Stanovich, K. E. (2013). Dual-process theories of higher cognition: advancing the debate. *Perspect Psychol Sci* 8, 223–241. doi: 10.1177/1745691612460685

Faul, F., Erdfelder, E., Lang, A.-G., and Buchner, A. (2007). G*power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* 39, 175–191. doi: 10.3758/BF03193146

Fitts, M., and Posner, M. I. (1967). *Human performance*, Belmont, CA, Brooks/Cole.

Furley, P., Schweizer, G., and Bertrams, A. (2015). The two modes of an athlete: dual-process theories in the field of sport. *Int. Rev. Sport Exerc. Psychol.* 8, 106–124. doi: 10.1080/1750984X.2015.1022203

Furley, P., and Wood, G. (2016). Working memory, attentional control, and expertise in sports: a review of current literature and directions for future research. *J. Appl. Res. Mem. Cogn.* 5, 415–425. doi: 10.1016/j.jarmac.2016.05.001

Gabbett, T. J., and Abernethy, B. (2013). Expert-novice differences in the anticipatory skill of rugby league players. *Sport Exerc. Perform. Psychol.* 2, 138–155. doi: 10.1037/a0031221

Gabbett, T. J., Wake, M., and Abernethy, B. (2011). Use of dual-task methodology for skill assessment and development: examples from rugby league. *J. Sports Sci.* 29, 7–18. doi: 10.1080/02640414.2010.514280

Gentile, A. M. (1972). A working model of skill acquisition with application to teaching. *Quest Monograph* 17, 3–23.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.

Gray, R. (2004). Attending to the execution of a complex sensorimotor skill: expertise differences, choking, and slumps. *J. Exp. Psychol. Appl.* 10, 42–54. doi: 10.1037/1076-898X.10.1.42

Green, A. L., and Helton, W. S. (2011). Dual-task performance during a climbing traverse. *Exp. Brain Res.* 215, 307–313. doi: 10.1007/s00221-011-2898-2

Hirsch, P., Koch, I., and Karbach, J. (2019). Putting a stereotype to the test: the case of gender differences in multitasking costs in task-switching and dual-task situations. *PloS One* 14:e0220150. doi: 10.1371/journal.pone.0220150

Hommel, B. (2020). Dual-task performance: theoretical analysis and an event-coding account. *J. Cogn.* 3, 1–13. doi: 10.5334/joc.114

Huestegge, L., and Strobach, T. (2021). Structuralist mental representation of dual-action demands: evidence for compositional coding from dual tasks with low cross-task dimensional overlap. *Acta Psychol.* 216:103298. doi: 10.1016/j.actpsy.2021.103298

Johnson, J. A. (2019). Taekwondo and Peace: How a Killing Art Became a Soft Diplomacy Vehicle for Peace. *Int. J. Hist. Sport* 35, 1637–1662. doi: 10.1080/09523367.2019.1618838

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, New Jersey: Prentice-Hall.

Kahneman, D. (2011). *Thinking fast and slow*. London, Penguin Books.

Kahya, M., Moon, S., Ranchet, M., Vukas, R. R., Lyons, K. E., Pahwa, R., et al. (2020). Brain activity during dual task gait and balance in aging and age-related neurodegenerative conditions: a systematic review. *Exp. Gerontol.* 128:110756. doi: 10.1016/j.exger.2019.110756

Kliegl, R., Smith, J., and Baltes, P. (1990). On the locus and process of magnification of age differences during mnemonic training. *Dev. Psychol.* 26, 894–904. doi: 10.1037/0012-1649.26.6.894

Koch, I., Poljac, E., Müller, H., and Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking—an integrative review of dual-task and task-switching research. *Psychol. Bull.* 144, 557–583. doi: 10.1037/bul0000144

Kramer, A. F., Larish, J. F., and Strayer, D. L. (1995). Training for attentional control in dual task settings: a comparison of young and old adults. *J. Exp. Psychol. Appl.* 1, 50–76.

Krampe, R. T., Smolders, C., and Doumas, M. (2014). Leisure sports and postural control: can a black belt protect your balance from aging? *Psychol. Aging* 29, 95–102. doi: 10.1037/a0035501

Leavitt, J. (1979). Cognitive demands of skating and stickhandling in ice hockey. *Can. J. Appl. Sport Sci.* 4, 46–55.

Leone, C., Feys, P., Moumdjian, L., D'amico, E., Zappia, M., and Patti, F. (2017). Cognitive-motor dual-task interference: a systematic review of neural correlates. *Neurosci. Biobehav. Rev.* 75, 348–360. doi: 10.1016/j.neubiorev.2017.01.010

Li, K. Z. H., Bherer, L., Mirelman, A., Maidan, I., and Hausdorff, J. M. (2018). Cognitive involvement in balance, gait and dual-tasking in aging: a focused review from a neuroscience of aging perspective. *Front. Neurol.* 9:913. doi: 10.3389/fneur.2018.00913

Li, K. Z. H., Krampe, R. T., and Bondar, A. (2005). "An ecological approach to studying aging and dual-task performance" in *Cognitive limitations in aging and psychopathology*. eds. R. W. Engle, G. Sedek, U. V. Hecker and D. N. Mcintosh (New York: Cambridge University Press).

Li, S.-C., Lindenberger, U., and Frensch, P. A. (2000). Unifying cognitive aging: from neuromodulation to representation to cognition. *Neurocomputing* 32-33, 879–890. doi: 10.1016/S0925-2312(00)00256-3

Li, K. Z. H., Lindenberger, U., Freund, A. M., and Baltes, P. B. (2001). Walking while memorizing: age-related differences in compensatory behavior. *Psychol. Sci.* 12, 230–237. doi: 10.1111/1467-9280.00341

Logan, S. W., and Fischman, M. G. (2011). The relationship between end-state comfort effects and memory performance in serial and free recall. *Acta Psychol.* 137, 292–299. doi: 10.1016/j.actpsy.2011.03.009

Logan, S. W., and Fischman, M. G. (2015). The death of recency: relationship between end-state comfort and serial position effects in serial recall: Logan and Fischman (2011) revisited. *Hum. Mov. Sci.* 44, 11–21. doi: 10.1016/j.humov.2015.08.003

Longman, D., Stock, J. T., and Wells, J. C. K. (2017). A trade-off between cognitive and physical performance, with relative preservation of brain function. *Nat. Sci. Rep.* 7:13709. doi: 10.1038/s41598-017-14186-2

Loprinzi, P. D., Blough, J., Crawford, L., Ryu, S., Zou, L., and Li, H. (2019). The temporal effects of acute exercise on episodic memory function: systematic review with meta-analysis. *Brain Sci.* 9:87. doi: 10.3390/brainsci9040087

Mac-Auliffe, D., Chatard, B., Petton, M., Croizé, A.-C., Sipp, F., Bontemps, B., et al. (2021). The dual-task cost is due to neural interferences disrupting the optimal spatio-temporal dynamics of the competing tasks. *Front. Behav. Neurosci.* 15:640178. doi: 10.3389/fnbeh.2021.640178

McMorris, T. (2016). Developing the catecholamines hypothesis for the acute exercise-cognition interaction in humans: lessons from animal studies. *Physiol. Behav.* 165, 291–299. doi: 10.1016/j.physbeh.2016.08.011

McMorris, T., and Hale, B. J. (2012). Differential effects of differing intensities of acute exercise on speed and accuracy of cognition: a meta-analytical investigation. *Brain Cogn.* 80, 338–351. doi: 10.1016/j.bandc.2012.09.001

Minarik, M. (2014). *Taekwondo zwischen Spektakel und ritual: Kampfkunst im sozialpolitischen Kontext (taekwondo as show or ritual: Martial arts in the context of society)*. Wien: Promedia Verlag.

Parker, H. (1981). "Visual detection and perception in netball" in *Vision and sport*. eds. I. M. Cockerill and W. W. Macgillivary (London: Stanley Thornes).

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychol. Bull.* 116, 220–244. doi: 10.1037/0033-2909.116.2.220

Plummer, P., and Eskes, G. (2015). Measuring treatment effects on dual-task performance: a framework for research and clinical practice. *Front. Hum. Neurosci.* 9:225. doi: 10.3389/fnhum.2015.00225

Roig, M., Nordbrandt, S., and Geertsen, S. S. (2013). The effects of cardiovascular exercise on human memory: a review with meta-analysis. *Neurosci. Biobehav. Rev.* 37, 1645–1666. doi: 10.1016/j.neubiorev.2013.06.012

Roig, M., Thomas, A. G., Mang, C. S., Snow, N. J., Ostadan, F., Boyd, L. A., et al. (2016). Time-dependent effects of cardiovascular exercise on memory. *Exerc. Sport Sci. Rev.* 44, 81–88. doi: 10.1249/JES.0000000000000078

Rouder, J. N., and Haaf, J. M. (2018). Power, dominance, and constraint: a note on the appeal of different design traditions. *Adv. Methods Pract. Psychol. Sci.* 1, 19–26. doi: 10.1177/2515245917745058

Schaefer, S. (2014). The ecological approach to cognitive-motor dual-tasking: findings on the effects of expertise and age. *Front. Psychol.* 5, 1–9. doi: 10.3389/fpsyg.2014.01167

Schaefer, S., and Amico, G. (2022). Table tennis expertise influences dual-task costs in timed and self-initiated tasks. *Acta Psychol.* 223:103501. doi: 10.1016/j.actpsy.2022.103501

Schaefer, S., Krampe, R. T., Lindenberger, U., and Baltes, P. B. (2008). Age differences between children and young adults in the dynamics of dual-task prioritization: body (balance) versus mind (memory). *Dev. Psychol.* 44, 747–757. doi: 10.1037/0012-1649.44.3.747

Schaefer, S., and Scornaienchi, D. (2019). Table tennis experts outperform novices in a demanding cognitive-motor dual-task situation. *J. Mot. Behav.* 52, 204–213. doi: 10.1080/00222895.2019.1602506

Schmidt-Kassow, M., Deusser, M., Thiel, C., Otterbein, S., Montag, C., Reuter, M., et al. (2013). Physical exercise during encoding improves vocabulary learning in young female adults: a neuroendocrinological study. *PloS One* 8:e64172. doi: 10.1371/journal.pone.0064172

Schmidt-Kassow, M., Kulka, A., Gunter, T. C., Rothermich, K., and Kotz, S. A. (2010). Exercising during learning improves vocabulary acquisition: Behavioral and Erp evidence. *Neurosci. Lett.* 482, 40–44. doi: 10.1016/j.neulet.2010.06.089

Schmidt-Kassow, M., Zink, N., Mock, J., Thiel, C., Vogt, L., Abel, C., et al. (2014). Treadmill walking during vocabulary encoding improves verbal long-term memory. *Behav. Brain Funct.* 10:24. doi: 10.1186/1744-9081-10-24

Schmiedek, F., Lövdén, M., and Lindenberger, U. (2010). Hundred days of cognitive training enhance broad cognitive abilities in adulthood: findings from the cogito study. *Front. Aging Neurosci.* 2, 1–10. doi: 10.3389/fnagi.2010.00027

Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D. E., Lauber, E. J., Kieras, D. E., et al. (2001). Virtually perfect time sharing in dual-task performance: uncorking the central cognitive bottleneck. *Psychol. Sci.* 12, 101–108. doi: 10.1111/1467-9280.00318

Shiffrin, R. M., and Schneider, W. (1977). Controlled and automatic human information processing: ii. Perceptual learning, automatic attending, and a general theory. *Psychol. Rev.* 84, 127–190. doi: 10.1037/0033-295X.84.2.127

Smith, M. D., and Chamberlin, G. J. (1992). Effects of adding cognitively demanding tasks on soccer skill performance. *Percept. Mot. Skills* 75, 955–961. doi: 10.2466/pms.1992.75.3.955

Somberg, B. L., and Salthouse, T. A. (1982). Divided attention abilities in young and old adults. *J. Exp. Psychol. Hum. Percept. Perform.* 8, 651–663. doi: 10.1037//0096-1523.8.5.651

Spiegel, M. A., Koester, D., and Schack, T. (2013). The functional role of working memory in the (re-)planning and execution of grasping movements. *J. Exp. Psychol. Hum. Percept. Perform.* 39, 1326–1339. doi: 10.1037/a0031398

Tomporowski, P., and Qazi, A. (2020). Cognitive-motor dual-task interference effects on declarative memory: a theory-based review. *Front. Psychol.* 11:1015. doi: 10.3389/fpsyg.2020.01015

Vuillerme, N., Danion, F., Marin, L., Boyadjian, A., Prieur, J. M., Weise, I., et al. (2001). The effect of expertise in gymnastics on postural control. *Neurosci. Lett.* 303, 83–86. doi: 10.1016/S0304-3940(01)01722-0

Vuillerme, N., and Nougier, V. (2004). Attentional demand for regulating postural sway: the effect of expertise in gymnastics. *Brain Res. Bull.* 63, 161–165. doi: 10.1016/j.brainresbull.2004.02.006

Wechsler, D. (1981). *Wechsler adult intelligence scale-revised (Wais-R)*, New York, Psychological Corporation.

Wickens, C. D. (2008). Multiple resources and mental workload. *Hum. Factors* 50, 449–455. doi: 10.1518/001872008X288394

Wollesen, B., and Voelcker-Rehage, C. (2019). Differences in cognitive-motor interference in older adults while walking and performing a visual-verbal Stroop task. *Front. Aging Neurosci.* 10:426. doi: 10.3389/fnagi.2018.00426

Zwaan, R. A., Pecher, D., Paolacci, G., Bouwmeester, S., Verkoeijen, P., Dijkstra, K., et al. (2018). Participant Nonnaiveté and the reproducibility of cognitive psychology. *Psychon. Bull. Rev.* 25, 1968–1972. doi: 10.3758/s13423-017-1348-y

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 22 December 2023
DOI 10.3389/fpsyg.2023.1330856

Check for updates

OPEN ACCESS

EDITED BY
Sabine Schaefer,
Saarland University, Germany

REVIEWED BY
Longxi Li,
University of Washington, United States
Pedro Gil-Madrona,
University of Castilla-La Mancha, Spain

*CORRESPONDENCE
Xavier García-Massó
✉ Xavier.garcia@uv.es

RECEIVED 31 October 2023
ACCEPTED 04 December 2023
PUBLISHED 22 December 2023

CITATION
Montalt-García S, Estevan I, Romero-Martínez J, Ortega-Benavent N, Villarrasa-Sapiña I, Menescardi C and García-Massó X (2023) Cognitive CAMSA: an ecological proposal to integrate cognitive performance into motor competence assessment.
Front. Psychol. 14:1330856.
doi: 10.3389/fpsyg.2023.1330856

Cognitive CAMSA: an ecological proposal to integrate cognitive performance into motor competence assessment

Sergio Montalt-García[1], Isaac Estevan[1], Jorge Romero-Martínez[1], Nuria Ortega-Benavent[1], Israel Villarrasa-Sapiña[2], Cristina Menescardi[1] and Xavier García-Massó[3]*

[1]AFIPS Research Group, Department de Didàctica de l'Educació Física, Artística i Música, Universitat de València, València, Spain, [2]HUMAG Research Group, Department d'Educació Física i Esportiva, Universitat de València, València, Spain, [3]HUMAG Research Group, Department de Didàctica de l'Educació Física, Artística i Música, Universitat de València, València, Spain

Purpose: To profile the participants using a system of self-organizing maps (SOM) based on their motor and cognitive performance during a dual-task version of the Canadian Agility and Movement Skill Assessment (Cognitive CAMSA).

Methods: A total of 169 secondary school students (39.3% girls) volunteered to participate. The original CAMSA, cognitive CAMSA, the Corsi and Digit Span tests were used to assess (a) motor competence, (b) motor competence with cognitive load, and (c) cognitive performance, respectively. SOMs and the *k*-means clustering algorithm were used to establish the adolescents' dual-task performance profiles.

Results: Including decision making based on verbal and visual cues in the original CAMSA significantly increased the participants' total scores but also the time required to complete the test, while the skill score remained unchanged. However, not all the participants showed changes in their performance in the same direction during the cognitive CAMSA. Person-centered analyses by SOMs and *k*-means clustering identified six performance profiles with variations in the cognitive, motor skill, and time scores ($H_5 = 146.15$, $H_5 = 102.68$, and $H_5 = 108.07$, respectively; all $p < 0.01$).

Conclusion: The cognitive CAMSA was shown to be a feasible field-motor test for assessing motor competence with a cognitive load in an ecological setting. Some of the profiles identified in the SOM approach represented adolescents with similar motor and cognitive performance in dual-task or single-task contexts, although other participants obtained high motor competence in single and dual-tasking while their cognitive performance declined or rose more in dual-task than in single task situations. The cognitive CAMSA emerges as a tool of great potential, applicable in educational and sports environments, to know subjects' characteristics and try to individualize the interventions accordingly with their dual-task profile.

KEYWORDS

motor competence, cognitive performance, physical literacy, dual-task, adolescent profiles

1 Introduction

The concept of Physical Literacy (PL) can be defined as the set of social, emotional and cognitive capacities to cooperate and communicate appropriately with the environment. It also requires a holistic commitment including integrated physical capacities in perception, experience, memory, anticipation, and decision making (Whitehead, 2001). PL currently refers to motivation, confidence, physical competence, knowledge, and understanding to value and take responsibility for engagement in physical activities for life (Cairney et al., 2019; Whitehead, 2019). PL also includes four interconnected domains, i.e., psychological, social, cognitive, and physical (Longmuir et al., 2015). Achieving appropriate levels of PL is a fundamental part of developing self-fulfillment, self-confidence, and positive self-esteem.

Physical education pays particular attention to motor competence, which is a key element in the PL domain. Although there is a wide variety of tests available to evaluate motor competence, they do have some limitations (Hulteen et al., 2020). Whereas isolated-based field-motor tests (e.g., the Gross Motor Development Test or the Körperkoordinations Für Kinder Test) are reliable enough in assessing motor competence, others are too far removed from the context in which fundamental movement skills are carried out (usually situations in sport that require a combination of skills). Circuit-based field-motor tests emerged as an alternative system of evaluating children's movement skills and their ability to combine simple movements to perform more complex movements [e.g., the Canadian Agility and Movement Skill Assessment (CAMSA); Longmuir et al., 2017]. However, as making decisions, which is inherent in practicing sport, is missing in the CAMSA it could be argued that this test do not measure motor competence in a completely ecological manner. Including perception tasks and decision making in the original version of the CAMSA test would be an interesting way of evaluating motor competence in an ecological setting as well as evaluating some of the PL cognitive elements (e.g., perceptual awareness or reasoning; Barnett et al., 2020).

To date, no test has been devised to concisely assess the cognitive domain. In fact, Cornish et al. (2020) states that the instruments used to measure PL usually focus on fundamental movement skills and are limited in measuring the cognitive domain (Robinson and Randall, 2017). It is also suggested that future research should attempt to explore and develop instruments to assess the cognitive domain objectively to understand motor development and PL holistically (Edwards et al., 2018). Cognitive tests are usually carried out to assess children's executive functions, such as working memory, inhibition, and cognitive flexibility (Diamond, 2013). However, these tests are performed in a sedentary context far removed from physical activity. As the results of these tests may possibly differ from the cognitive performance during physical activity, we therefore considered it would be of interest to develop an instrument capable of evaluating elements in the cognitive domain when carrying out motor competence tests.

Combining cognitive and physical tasks in the same test seems to be the key to creating a method of ecologically determining PL cognitive level and performance, while dual-tasking (DT) is an already existing paradigm in which motor and cognitive tasks are carried out simultaneously and the effect of the interactions between them on performance are studied (Bustillo-Casero et al., 2017). DT is used in laboratory settings but its usefulness in more ecological environments is still unknown. Tests that include simultaneous motor and cognitive tasks could be used to assess cognitive function and motor competence ecologically. It is also of interest to design tools that allow PL to be assessed holistically, or at least gradually incorporate multiple domains simultaneously. Using DT to assess both motor and cognitive performance in the same field test would be a breakthrough in achieving this goal.

Even though it is important to consider that the interference generated by performing two tasks at the same time may affect the students who are proficient in performing simple tasks and who may not be as proficient in a DT, different interaction patterns have been found between tasks during DT. In these models, we find three different theories to explain DT interference (Lacour et al., 2008; Bonnet and Baudry, 2016; Wollesen et al., 2016). These include the cross-domain competition model (two tasks performed simultaneously or in quick succession, requiring the same or overlapping cognitive processes), the inverted U-shaped nonlinear interaction model (the optimal level of task difficulty that allows efficient multitasking, while both easier and more difficult tasks can result in reduced performance), and the prioritization model (faced with multiple tasks, individuals allocate most attention to the most important at a given time while reducing the resources allocated to the lower-priority task). These three models emerged as the outcomes of divergent results in different DT studies (Lacour et al., 2008; Bonnet and Baudry, 2016; Wollesen et al., 2016; Bustillo-Casero et al., 2020). The divergence in the findings could have been the result of the subjects' individual strategies to deal with the DT. In fact, we do not know how factors like age or task difficulty can influence performance during DT (Schaefer, 2014; Bustillo-Casero et al., 2017; Marco Ahulló et al., 2022).

The aim of this study was thus to design and test a new version of the CAMSA that included decision-based verbal and visual cues (i.e., cognitive CAMSA) to assess both motor competence and cognitive performance, plus the impact of the cognitive load in motor competence in an ecological setting. To achieve this, the interference in the students' performance in the variables derived from the original CAMSA (i.e., motor skill score, time score, and total score) when performing the cognitive version of the test was first determined. It was thus possible to observe whether the students responded differently when performing the traditional test compared to the cognitive CAMSA in the motor domain. On confirming that not all the students responded in the same way to a DT, the second objective was to establish the student profiles based on the variables derived from the cognitive CAMSA (i.e., cognitive score, motor skill score, and time spent). The third objective was to determine the differences between the performance profiles in single cognitive tasks, single motor tasks, performance during DT, and gender, which would allow us to determine whether the PL cognitive and motor tests using DT aligned with the results of single tests. If we confirmed that different results were obtained in DT and single tasks, it would open up a discussion about the suitability of DT-based tests to assess cognitive and motor performance. DT could thus provide a more ecological assessment and would better represent what actually happens during physical activities and sports.

2 Materials and methods

2.1 Participants

One hundred and sixty-nine secondary school students (39.3% girls) volunteered to participate during the 2021–2022 academic year in this cross-sectional study. The participants' characteristics can be seen in Table 1. All the participants performed all the tests (i.e., the original CAMSA, cognitive CAMSA, Corsi and Digit Span tests). The sample was selected from three secondary schools of urban areas in the province of Valencia near Valencia city (Valencia Community, Spain). Those students with cognitive or physical impairments that prevented them from performing the different tests or that could pose a risk to their health were also invited to participate, but were excluded from the statistical analyses.

The students' parents or guardians provided signed informed consent forms before the study, and the participants gave their assent orally. The procedures conducted in the study were performed in accordance with the Helsinki Declaration, and the study was approved by the Ethical Committee of the University of XXX (Code 1259844).

2.2 Procedures

The researchers first contacted the school principals to explain the study and request their participation. The families were informed about the nature of the project and once they had given their written consent, the measurement protocol was carried out. To complete all the tests, the participants performed two experimental sessions separated by at least 24 h. The CAMSA and Corsi tests were carried out in one session, while the cognitive CAMSA and Digit Span tests were included in the other. The order of the sessions was counterbalanced within the schools to minimize any potential order effects, i.e., whereas the students in one classroom performed the tests in the same order, those in another classroom performed the test in the reverse order (i.e., first the cognitive CAMSA and Digit Span test, followed by the original CAMSA and Corsi tests).

For the completion of both the cognitive and original CAMSA tests, the students were instructed to complete the assessment as quickly as possible while performing the skills to the best of their motor competence. In line with the original procedure, two demonstration trials were provided for each participating class. The first demonstration was performed by a research assistant familiar with the CAMSA test, while explaining each skill thoroughly. The second demonstration was performed by the same research assistant to indicate the effort and speed required to carry out the test. Each student performed two familiarization trials and two formal trials, which were coded *ad hoc*. During the familiarization trials, verbal cues were used only to remind the participants of the next task to be performed, in an attempt to minimize the impact of memory on the task sequence and completion time. These cues consisted of indicating aloud the next task to be performed (e.g., "throw the ball"). The timing began with the command "go" and ended when the participant kicked the soccer ball (Estevan et al., 2023). The time required to perform the original CAMSA test ranged from 14 to 47 s, and the mean completion time being 22.73 ± 5.57 s. During the assessment trials, no feedback was provided on the task performance and no attempt was made to encourage task performance or affect the learner's performance in any way. In accordance with the protocol (Longmuir et al., 2017), the score of the best attempt was used to calculate the motor competence scores.

TABLE 1 Participants' sociodemographic characteristics.

Sex	Age (years)	Weight (kg)	Height (m)
Girls	13.07 (0.74)	50.1 (9.95)*	1.59 (0.06)*
Boys	13.3 (1.02)	54.53 (10.9)	1.65 (0.09)
All	13.2 (0.85)	52.5. (10.7)	1.62 (0.08)

*indicate significant differences between girls and boys ($p < 0.05$).

The cognitive CAMSA followed the same procedure as the original CAMSA in terms of the students' performance. In this case, the time taken to perform this test ranged from 15 to 53 s (average 25.36 ± 7.05 s). Both the original and cognitive CAMSA were performed in the school yard. There were some slight modifications in the cognitive CAMSA related to participants' cognitive performance during motor performance as decision-making events and minor adjustments to the test equipment (i.e., differences in hoop colors, placing throwing targets, and variations in shooting at goal). The cognitive tests were performed in silent classroom using a laptop and open-source software Psychology Experiment Building Language (Mueller and Piper, 2014). The participants received a series of instructions provided automatically by the program for the completion of the tasks, while any doubts were answered by the researcher. The cognitive tasks were conceptualized as measures of executive functions, as in previous studies (Cooper et al., 2016; Pontifex et al., 2019).

2.3 Measurements

2.3.1 Cognitive single tests

The Digit Span test, adapted from Wechsler (1949), evaluates working memory and consists of remembering a sequence of numbers presented to the participants and repeating it in the same order (i.e., Digit Span Forward). Since the digital version of the test was used, the numbers were displayed for 1 s on a laptop screen, with a 1-s interval before the next number. The subjects then had to repeat the complete sequence on the laptop. The length of the sequence of numbers starts at three digits and is gradually increased. Two attempts can be made to repeat the numbers. The test is ended when a participant fails both attempts or when they reach the maximum length of 10 numbers. The total number of correct sequences and the longest correctly recalled numerical sequence (i.e., Block Span) were taken as the test outputs. This test has shown moderately high reliability in children aged 6–12 years old (Alloway et al., 2008; Flanagan et al., 2011).

The Corsi test, based on the Digit Span Test (Kessels et al., 2000) was designed to evaluate visuospatial working memory and consists of remembering a sequence of ordered blocks that appear on a computer screen. The procedure steps included (i) nine blocks in pseudorandom positions; (ii) one block is illuminated during 1 s; (iii) a transient period of 1 s between the stimuli; (iv) second block is illuminated; (v) the procedure continues until the number of blocks reach the maximum sequence length; (vi) the subjects indicate the illuminated blocks by clicking on them with the mouse in the correct order. Two familiarization sequences were first performed, in which three blocks were illuminated, after which the test started with a sequence of two blocks. As in the Digit Span test, the participants were allowed two attempts at each sequence. If they failed both attempts or reached the maximum block sequence of nine blocks the test was ended. The scores obtained were the longest correctly recalled sequence (Block Span), the number of correct attempts and the memory span [minimum sequence length (i.e., 2), added to the number of correct attempts, divided by the number of trials in each sequence length (i.e., 2)].

2.3.2 Motor competence

The CAMSA consists of a series of seven movement skills that are completed in a continuous sequence (Menescardi et al., 2022). These skills include three two-footed jumps, sliding along a 3-m distance, returning, catching, and throwing a ball at a wall-mounted target 5 m away, skipping 5 m, performing a one-footed hop in and out of six hoops, and kicking a ball between two cones 5 m apart. The assessment of the children's performance in the CAMSA involves two key criteria: the time required to complete the circuit (product-based) and the quality of the movement pattern executed or the motor skill score (process-based). The time taken to complete the circuit is recorded and transformed into a point score, known as the time score, ranging from 1 to 14 (Longmuir et al., 2017). Higher values indicate a shorter time taken to complete the circuit. The quality of movement is assessed by 14 skill performance criteria, with one point awarded for each criterion completed correctly, resulting in the skill score (Longmuir et al., 2017). Combining the product and process scores, a total CAMSA score of 28 points is obtained (Longmuir et al., 2017). The best score of two trials is considered for evaluation. The CAMSA has been validated in Spain among students in Primary and Compulsory Secondary Education, as described in Menescardi et al. (2022).

2.3.3 Simultaneous motor competence and cognitive performance

The Cognitive CAMSA was based on the original version of the test with the same motor skills. The changes included were related to the cognitive performance of the participants during the motor performance, with some minor changes to the test equipment including: (i) the three hoops on the left were yellow and the three on the right were blue, (ii) there were two throwing targets in front of the participants with one slightly to the left and the other to the right, and (iii) there were two goal posts, one with yellow cones and the other with blue (Figure 1).

Four decision making events were included in the cognitive assessment: (i) before beginning, the researcher showed a blue or yellow card and the subjects performed the three two-footed jumps inside the hoops of the other color, with 0 or 1 point for a fail or correct performance, respectively; (ii) during the sliding test, the researcher gave some simple numbers to be added before throwing either at the right-hand target if the result was even or at the left-hand target if it was odd, with either a 0 or 1 point for a fail or correct performances respectively; (iii) in skipping, the researcher indicated two numbers to the participants, the first referring to the hoop they should use to start the next motor test (i.e., one-footed jumps) and the second indicated the last hoop in the activity, with 0, 1, or 2 points according to two fails, or to one or two correct performances, respectively; and (iv) after the one-footed jumps, the researcher showed a yellow or blue card and the participants had to kick the ball at the color not shown, with a 0 or 1 point score according to a fail or one or two correct performances, respectively. The cognitive score (from 0 to 5) was the total score, i.e., 0 if no decisions were taken correctly and 5 if all the decisions were correct.

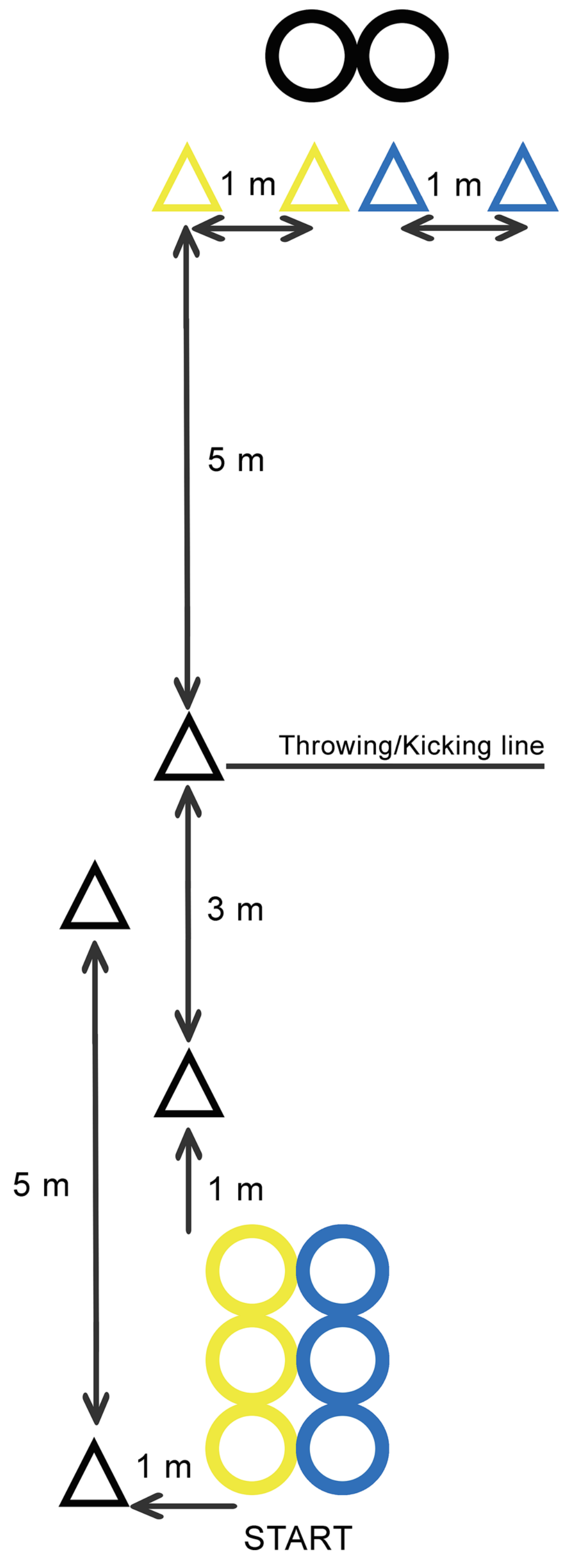


FIGURE 1
Cognitive CAMSA schedule.

2.4 Data analysis

The differences in the skill score, time spent, and total score between the original and cognitive CAMSA were first compared using the Wilcoxon signed rank test. DT interference was then computed (Bustillo-Casero et al., 2017) and represented in boxplots (Oliver et al., 2018) that were influenced by dual tasking.

After determining that not all the adolescents had been similarly affected by dual tasking, the profiles of the DT performance were determined, for which the cognitive score, the skill score, and the time spent in the cognitive CAMSA were included as input variables in a SOM analysis. This analysis was computed on the Matlab R2021a Program (Mathworks Inc., Natick, United States) and the SOM Toolbox (Version 2.0 Beta) for Matlab (Vesanto et al., 1999).

The SOM analysis was used to classify the participants and provide profiles of their similarities in terms of the dependent variables in a three-step procedure (Pellicer-Chenoll et al., 2015), including: (i) the construction of the neuron network (i.e., 11 × 6 neurons map), (ii) the initialization, in which the value or weight of each input variable was assigned to each neuron in two different ways (i.e., randomized and linear initialization), and (iii) a training step to modify the values or weights of the neurons initially assigned by two different training algorithms (i.e., sequential and batch; Oliver et al., 2018).

Several factors influence the modification of the neuronal weights in each iteration during the training. An input vector (i.e., a study case or subject) is entered in the network, after which the neurons in the lattice "compete" to win the input vectors by achieving the smallest Euclidean distance between its weight vector and the input vector, so that the weight vector of the winning neuron has the closest values to the cases in the neuron. All the neurons in the lattice then adapt their weight values closer to the input vector values. The magnitude of the adaptation depends on two processes: (a) the learning ratio, which has a high value at the start of the training process, which is gradually reduced as the training proceeds; (b) the neighbor function, which determines the adaptation of the winning neuron and the rest of the neurons. The adaptation magnitude is negatively associated with the distance between the neuron and the winner. This process is repeated until the training process ends (Pellicer-Chenoll et al., 2015).

Since the final analysis depends on the random procedure (e.g., initialization and entry order of the input vector), the above-described process was repeated 100 times to increase the odds of finding the best solution. 1,600 SOM were obtained in this way because two different training methods, four neighborhood functions and two initialization methods were used (i.e., 100 × 2 × 4 × 2). After multiplying the quantization and topographical errors, the map with the minimum error was then chosen (Pellicer-Chenoll et al., 2015).

After the SOM analysis, a *k*-means method was used to classify the neurons into larger groups, according to the input variables' characteristics. The number of clusters was set to range between 2 and 10 to avoid an excessive number of profiles. The final number of clusters was the one with lowest Davies-Bouldin index, which were used to describe individual profiles according to the input variables.

The clusters were lastly compared for both the input variables included in the SOM and by gender and single-task performance. The Corsi output variables (i.e., total correct trials, Block Span, and Memory Span), Digit Span (i.e., total number of correct sequences and Memory Span), and original CAMSA (i.e., motor skill score, time to complete the test, and total score) tests were compared between the clusters using the Kruskal-Wallis test with the Dunn test for pairwise comparisons. The Chi-Squared test was used to detect significant associations between cluster membership and gender, with the level of significance set to $p = 0.05$.

3 Results

3.1 Dual-task interference in the cognitive CAMSA

All the descriptive data of the variables used in this study are provided in Supplementary material. The results indicate that including cognitive tasks (i.e., decision making) in the cognitive CAMSA significantly reduced the total score while it increased the time spent (Figures 2D,G). Compared to the original CAMSA, the cognitive CAMSA motor skill score therefore did not change significantly (Figures 2A,B). Dual tasking during the cognitive CAMSA thus did not change the students' motor skill score, whereas the time required to perform the test increased. However, when the DT interference is analyzed (Figures 2E,H), it can be seen that not all the participants had better scores in the original CAMSA (Figure 2I) or increased the time spent in the task (Figure 2F). 14% of the subjects had a higher total score in the cognitive CAMSA than in the original version, whereas 73% had lower total scores and the remaining 12% did not change theirs (Figure 2I). Furthermore, 82% of the subjects required a longer time in the cognitive CAMSA than in the original, while 17% reduced the time spent and the remaining 1% did not require the same time. Although no significant differences were found between the original and cognitive CAMSA in the motor skill scores, in Figure 2C, it can be seen that 22% of the subjects increased their motor skill scores in the cognitive CAMSA, 22% showed no change, while 56% showed a loss of performance (Figures 2B,C,E,H).

3.2 Performance profiles of cognitive CAMSA

According to the SOM approach and *k*-means cluster algorithms, using the cognitive CAMSA scores (i.e., cognitive score, skill score, and time spent) as input variables, six performance profiles were obtained (Figure 3). In other words, these six profiles are related to the participants' performance in a DT situation. The association between cluster and gender was not significant ($\chi^2_5 = 10.3$; $p = 0.06$), clusters 4 and 5 having a higher percentage of males, while clusters 1 and 2 were composed of a higher proportion of girls than boys.

A main effect of cluster membership was found on cognitive score ($H_5 = 146.15$; $p < 0.01$), motor skill score ($H_5 = 102.68$; $p < 0.001$), and time spent ($H_5 = 108.07$; $p < 0.001$). Pairwise comparisons revealed that clusters 3 and 5 reported the highest cognitive performance, which, like cluster 2 showed the lowest cognitive performance. Clusters 4, 5, and 6 showed higher values than clusters 1, 2, and 3 in the motor skill score, while the time spent for those in cluster 1 was longer than the rest of the participants in other clusters. The individuals in cluster 5 obtained a higher time spent than those in clusters 2, 3, and 4, while those in cluster 2 required a longer time than those in cluster 6.

3.3 Differences between clusters in single task performance

The results revealed a significant effect of cluster membership on the motor skill score ($H_5 = 48.46$; $p < 0.001$), time score ($H_5 = 80.28$; $p < 0.001$), and total score ($H_5 = 93.01$; $p < 0.001$) in the original CAMSA

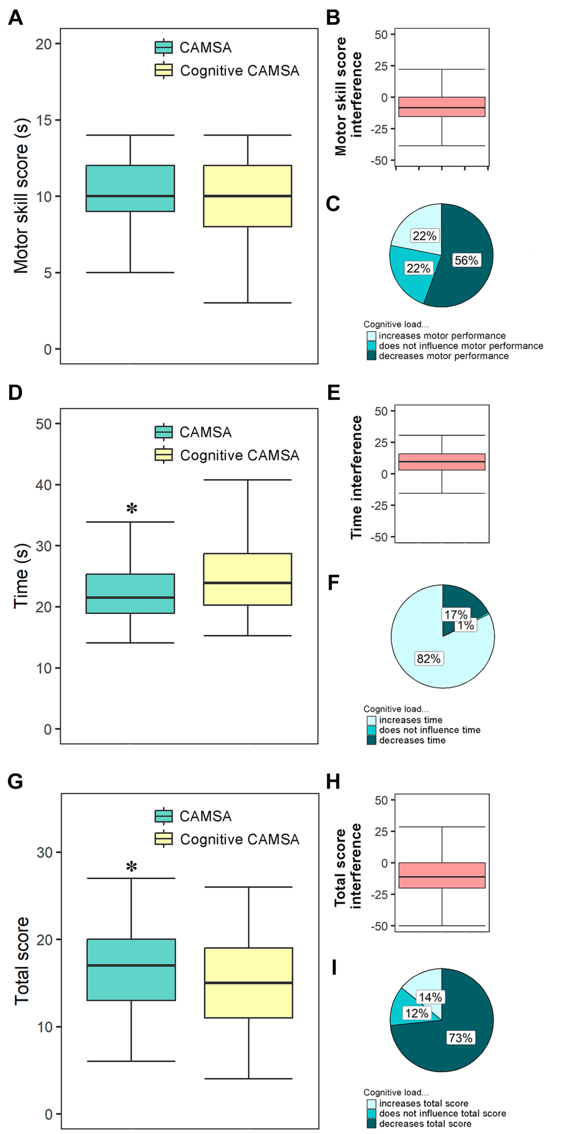


FIGURE 2
Dual-task interference during the performance of CAMSA test. Layers **(A,D,G)** show box plots of the values obtained in the motor skill score, time, and total score variables both on cognitive and original CAMSA, respectively. Layers **(B,E,H)** show box plots of the interference in the motor skill score, time and total score variables when performing dual tasks (i.e., cognitive CAMSA) compared to when performing single tasks (i.e., original CAMSA) respectively. Layers **(C,F,I)** show the percentage of participants who increase, decrease, or do not change their scores on the variables motor skill score, time, and total score when performing the cognitive CAMSA compared to the original CAMSA, respectively. *indicates significant differences ($p < 0.05$).

test. Pairwise comparisons (Figure 4) showed that clusters 4, 5, and 6 had higher motor skill scores than cluster 1, while cluster 5 had a higher motor skill score than clusters 2 and 3. In the time score, the participants in clusters 5 and 6 were faster than those in clusters 1 and 2, while clusters 3 and 4 were slower than cluster 5. The total original CAMSA score was also lower in cluster 1 than in 4, 5, and 6, while clusters 5 and 6 showed higher values than 2. The values of those in clusters 3 and 4 were lower than those in cluster 5.

In cognitive performance, there was a main effect of cluster membership on the total correct trials ($H_5 = 17.15$; $p < 0.004$), block span ($H_5 = 16.47$; $p < 0.006$), and memory span ($H_5 = 15.61$; $p < 0.008$) obtained in the Corsi Block test. Pairwise comparisons (Figure 4) revealed that cluster 5 had higher values in total correct trials, block span and memory span than cluster 1. The rest of the clusters showed no significant differences. In Supplementary material, all the pairwise comparisons as well as effect sizes are available.

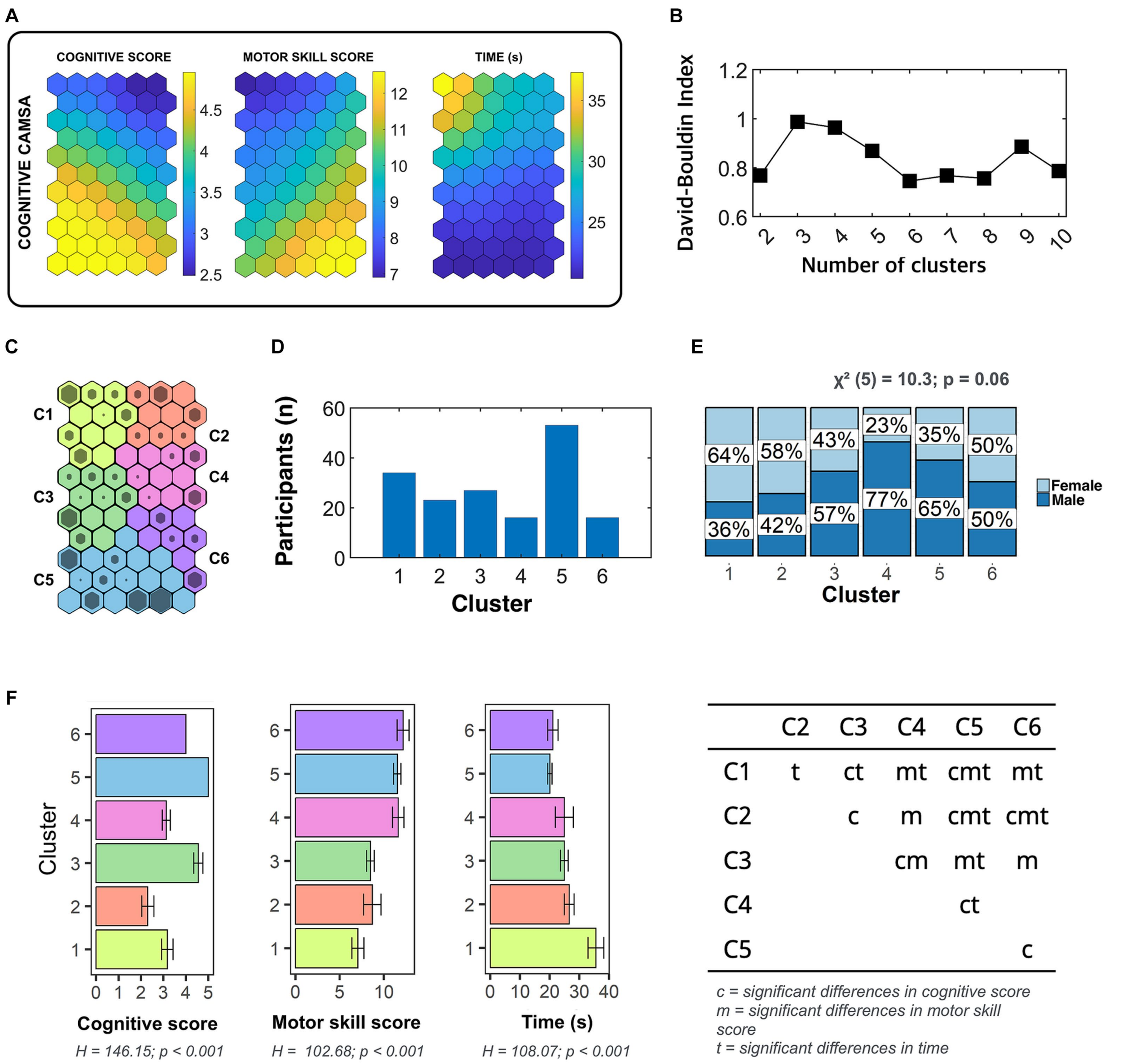
A main effect of cluster membership was found on the total number of correct sequences ($H_5 = 11.73$; $p = 0.039$) in the digit span test, while pairwise comparisons revealed no significant differences between the cluster although accordingly with the *r*-effect size small-to-medium effects were found between cluster 1 and cluster 4, 5, and 6 in both variables (Supplementary material).

4 Discussion

Including cognitive demands (e.g., decision making) into field-motor tests could provide a new insight into the motor competence assessment field because, as the setting is maintained, cognitive performance can be assessed in an ecological environment just like active games. The purpose of the current study was thus to design and test a cognitive CAMSA, which includes decision making-based verbal and visual cues in order to assess both motor competence and cognitive performance and to analyze the impact of a cognitive load on motor competence in an ecological setting. In general, and in comparison with the original CAMSA, there were no significant differences in the motor skill score during the application of the cognitive CAMSA. However, the time spent increased, resulting in lower marks in the total score. Interestingly, these results vary widely among the participants in the current study; for instance, some improved their motor skill score (22%), while others did not (22%) or reduced their motor skill score (56%). The same occurred with the time spent, with most the participants increasing the time spent (82%), some reducing it (17%), and a small minority obtaining a similar time (less than 1%). Previous studies have shown an increase in motor performance during DT application, to the detriment of cognitive performance (Schaefer et al., 2008). Other studies have shown how DT motor performance can decline, such as Palluel et al. (2010) and Olivier et al. (2010), who found reduced postural control in adolescents and children, respectively, in a DT compared to simple tasks. The effect of a cognitive load added to a motor task on performance still remains unclear, due to the diversity in the results obtained. However, all these previous results have the defect of considering that DT affects everybody in the same way, the present study being the first to analyze DT interference in a person-centered approach.

From our results it can be concluded that a DT does not affect everyone in the same way. The variables analyzed by the cognitive CAMSA included in the SOM gave rise to six profiles, including several profiles that deserve to be highlighted. The cluster 5 scores excel in both cognitive and motor competence, whether evaluated in isolation or by means of the cognitive CAMSA test, which is considered to be a DT setting. Similarly, cluster 1 shows a lower performance than the rest in both cognitive and motor competence, whether single or dual tasks. Profiles 1 and 5 include the highest number of participants.

It is interesting to note the existence of a profile (Cluster 2) that shows better cognitive performance during seated tests, with a reduced performance in the cognitive CAMSA (i.e., in a DT). In this



	C2	C3	C4	C5	C6
C1	t	ct	mt	cmt	mt
C2		c	m	cmt	cmt
C3			cm	mt	m
C4				ct	
C5					c

FIGURE 3
Results derived from Self-Organizing Map analysis in which performance profiles during cognitive CAMSA are described. Panel **(A)** shows the component planes resulted from Self-Organizing Maps analysis on cognitive score, motor skill score, and time spent in complete cognitive CAMSA. Panel **(B)** indicates the Davies-Bouldin index associated with k-means cluster algorithm applied to obtain profiles. Panel **(C)** shows the six clusters obtained using k-means algorithm with the lowest Davies-Bouldin index. Panel **(D)** reports the number of participants allocated in each cluster. Panel **(E)** shows the percentage of girls and boys in each cluster and the chi-square test results. Panel **(F)** represents the mean and standard deviation of each cluster in each of the variables obtained from cognitive CAMSA as well as Kruskal-Wallis test results. Pairwise comparisons are reported in the table of the layer **(F)**, where each letter (i.e., c, m, and t) indicates in which variable significant differences between clusters were obtained.

profile, the individuals exhibited the appropriate levels of motor competence in both the original and cognitive CAMSA. The cognitive CAMSA could be considered as an adequate stimulus to increase the cognitive effort in this type of profile, given the contrasting performances in cognitive CAMSA (DT) and isolated cognitive tasks. On the other hand, it should be noted that a profile (Cluster 3) emerged that stands out for its cognitive performance during the cognitive CAMSA, but not in the simple cognitive tasks. Profile 3 suggests the need to improve motor skills in tasks with a high cognitive load. In terms of cognitive performance, there are groups with heterogeneous levels of cognitive performance in DT and simple tasks. It should be noted that limited significant differences were found between profiles in seated cognitive test. This can be due to a statistical type II error due to a reduced sample size of each cluster. In Supplementary material, some small-to-medium effect size between cluster 1 and clusters 4, 5, and 6 were found in digit span test variables. Future works would check if increasing the sample size of the clusters the differences between them emerge as significant.

While some students (profiles 5 and 6) showed good cognitive performance in the DT and the simple task, others (profile 2) performed worse in the cognitive tasks during DT than in simple tasks, or vice versa (profile 3). Studies by Howell et al. (2016) and

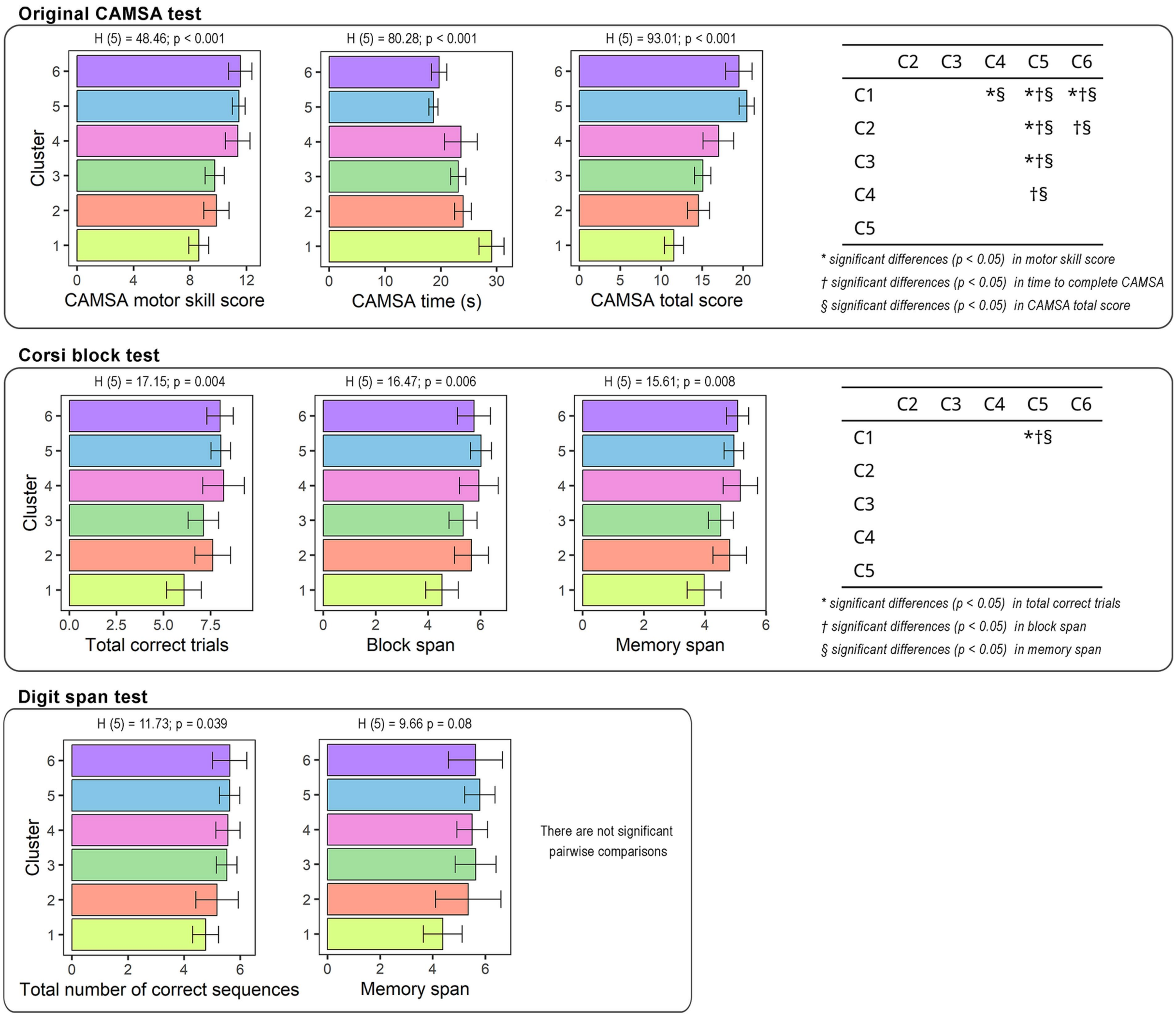


FIGURE 4
Differences in the variables obtained from original CAMSA, Corsi Block test, and Digit Span test between clusters.

Madehkhaksar and Egges (2016) concluded that the complexity of cognitive tasks can influence motor performance during the execution of a DT. On the one hand, Estevan et al. (2018) found reduced performance in motor and cognitive tasks in adolescents as the DT cognitive requirements were increased. On the other hand, Bustillo-Casero et al. (2020) detected better adaptation of postural control in DT as the difficulty level of the cognitive task was raised. So far, no single model has been found to explain DT interference, since it affects individuals differently according to unknown factors, which prevents generalizing theoretical models to the whole population. The cognitive CAMSA seems to emerge as a key tool that enables the precise assessment of student DT performance in order to implement the most suitable learning strategies in schools, as it helps us to accurately identify our students' characteristics.

As indicated in the previous paragraph, static and moving cognitive assessment are not clearly equivalent, similar to previous research. In the study by Brilliant et al. (2021), discordance between static and moving cognitive test scores was observed. On the other hand, Ramos-Nuñez et al. (2017), confirmed that different executive functions contribute to task performance depending on task difficulty, with modularity being involved in simple tasks and cognitive flexibility in complex tasks. There have been found profiles that perform isolated cognitive tasks correctly, but not during a DT (Cluster 2) and vice versa (Cluster 3), in line with previous studies (Schaefer et al., 2008; Palluel et al., 2010; Howell et al., 2016; Bustillo-Casero et al., 2017). Trying to measure the PL cognitive domain by means of a DT situation (motor competence with a cognitive load) instead of a seated cognitive test may be recommended, since it more closely resembles a real sports situation. In this regard, the cognitive CAMSA allows us to assess a cognitive performance during motor tasks and at the same time make a global motor competence assessment (total score) similar to the one performed in the original CAMSA.

Although there were no significant differences in the men/women ratio in the profiles obtained, this aspect requires attention, since the trend toward significance has been found. As can be seen, some profiles have a higher prevalence of males or females that exhibited clearly distinctive characteristics. The frequency of males in clusters 4 and 5, which have medium to high levels of motor skill scores, both in DT and in isolation (i.e., cognitive CAMSA and original CAMSA) is higher than females, while females appeared associated with cluster 1, with lower levels in the afore-mentioned skills. One reason why motor competence seems to be influenced by gender is that males tend to participate more regularly in physical activity during the early stages (Boraita et al., 2020; Kallio et al., 2020; Abid et al., 2021). This could be attributed to gender-related social conditioning, which could lead to an erroneous physical self-perception and a negative predisposition to sports participation in girls (Cavallo et al., 2015; Corr et al., 2019; Sabiston et al., 2019) and in turn provide women with fewer opportunities to develop motor competence. It thus seems essential to equalize the gender participation in sports activities and to improve female students' physical self-perception. These findings highlight the need for educational interventions that equalize the results of boys and girls. It is noted that the context conditions females, as in early childhood boys and girls tend to show similar results in motor skills, which can be even higher in the female gender (Rodríguez-Guerrero et al., 2023). Therefore, implementing programs to encourage girls to take up physical activity may be key to achieving this goal (Aguilar Jurado et al., 2018). In addition, the professional training of teachers is a factor that can have a strong influence on the development of motor skills in early childhood for both boys and girls (Honrubia Montesinos et al., 2023).

As has been noted, since different factors can influence performance when carrying out a DT, it seems necessary to examine additional factors which in theory are not considered during its assessment. Those with a more developed PL (frequently those with more sports experiences) are likely to obtain higher motor competence scores (Seidler, 2004; Li et al., 2007; Yang, 2015) and probably also cognitive performance during a motor task. Each individual's functional perceived difficulty of a task could also be a conditioning factor (Li et al., 2007; Goldhammer et al., 2014; Akizuki and Ohashi, 2015; Aljamal et al., 2019). It is also possible that different people carry out the same task with more or less effort, and this should be taken into account when evaluating a DT. In addition to enjoyment, it is also important to mention the motivation involved in the task. Those who show greater motivation to perform a DT make a greater effort to improve their performance (Ainley, 2006; Li et al., 2007; Shin and Grant, 2019). In future research, it would be interesting to measure all these factors to obtain results closer to DT evaluation in a more realistic way.

Like most, this study is not without its limitations. Despite the fact that previous studies have shown differences by gender in the levels of motor competence (Boraita et al., 2020; Kallio et al., 2020; Abid et al., 2021), no significant association between clusters and gender were found in the present study. This divergence can be due to the fact that we are conducting a person-centered approach while previous studies perform the analysis on a variable-centered approach. Secondly, the lack of a specific scoring scale for the cognitive CAMSA (including relative time score) reduced the total score. Future research should consider the application of a separate scale for cognitive CAMSA scoring in this way. Furthermore, it should be noted that in the cognitive tasks of the cognitive CAMSA there is the possibility that a motor error may occur instead of a cognitive error. For example, it is possible that some participants resolved correctly the question about to what target to throw the ball but technically they fail and hit the incorrect target. This has been categorized as a cognitive error but actually it is a motor skill mistake. It should be noted that of the five cognitive decisions to be made, a motor error is only possible in two (throwing and kicking). Moreover, the authors consider that this error is marginal and does not significantly affect the results obtained. Nevertheless, as an alternative, it would be interesting to ask participants to comment aloud on the side of the throw and kick before performing it. Finally, an important area for attention is the need for extensive validity and reliability testing of the Cognitive CAMSA. The lack of extensive validation and reliability testing may limit the consistency and accuracy of the instrument in providing results across different demographic groups and over time. The recognition of this requirement for further validation and reliability testing underlines the need for future research to ensure a full understanding and robustness of the Cognitive CAMSA as an assessment tool.

Regarding the study's practical applications, we can highlight on one hand the design of the cognitive CAMSA, which assessed not only motor competence, but also cognitive performance. The cognitive CAMSA could thus be applied in physical education to assess these two PL aspects in secondary school students and also whether it improves over time. We were also able to determine the profiles of adolescents in performing the cognitive CAMSA and to classify individuals into these profiles to determine their general characteristics and any aspects that should be empowered. For example, a student who performs the cognitive CAMSA and is placed in cluster 5 will be an adolescent with high DT performance (both cognitive and motor competence) but will also perform well when executing the tasks separately. In view of these results, educational interventions should be considered in physical education based on improving motor and cognitive performance in DTs.

5 Conclusion

In conclusion, a cognitive version of the CAMSA was designed and tested for assessing both motor and cognitive performance, which are elements in the physical and cognitive PL domains. We found that the interference generated by the cognitive CAMSA did not affect all the adolescents equally, i.e., we found six student profiles based on their motor competence and cognitive performance. Some of these profiles belonged to adolescents with a similar performance in both DT and single-task contexts (e.g., cluster 5 and 6). However, others showed high motor competence in single and dual tasking while their cognitive performance declined (e.g., cluster 4) or increased (e.g., cluster 3) in DT compared to single tasks. Adolescents will benefit from the cognitive CAMSA because it allows them to be grouped by their performance and any aspects that require to be fostered.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Ethics committee of the University of Valencia. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

SM-G: Data curation, Investigation, Methodology, Visualization, Writing – original draft. IE: Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing. JR-M: Data curation, Investigation, Methodology, Writing – review & editing. NO-B: Formal analysis, Investigation, Validation, Writing – review & editing. IV-S: Methodology, Resources, Validation, Writing – review & editing. CM: Conceptualization, Data curation, Project administration, Writing – review & editing. XG-M: Formal analysis, Funding acquisition, Resources, Software, Supervision, Visualization, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This research was funded by the Spanish National Research Agency (PID2020-115075RA-I00 by the MCIN/AEI/10.13039/50110001) and the Conselleria de Educación, Universidades y Empleo. Generalitat Valenciana (Award number: AICO/2022/185).

Acknowledgments

The authors are grateful to all the participating schools' heads, students, parents, and teachers for their co-operation.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1330856/full#supplementary-material

References

Abid, R., Ammar, A., Maaloul, R., Souissi, N., and Hammouda, O. (2021). Effect of COVID-19-related home confinement on sleep quality, screen time and physical activity in Tunisian boys and girls: a survey. *Int. J. Environ. Res. Public Health* 18:3065. doi: 10.3390/ijerph18063065

Aguilar Jurado, M. A., Gil Madrona, P., Ortega Dato, J. F., and Rodríguez Blanco, Ó. F. (2018). Mejora de la condición física y la salud en estudiantes tras un programa de descansos activos. *Rev. Esp. Salud Publ.* 92, e1–e10. PMID: 30178781

Ainley, M. (2006). Connecting with learning: motivation, affect and cognition in interest processes. *Educ. Psychol. Rev.* 18, 391–405. doi: 10.1007/s10648-006-9033-0

Akizuki, K., and Ohashi, Y. (2015). Measurement of functional task difficulty during motor learning: what level of difficulty corresponds to the optimal challenge point? *Hum. Mov. Sci.* 43, 107–117. doi: 10.1016/j.humov.2015.07.007

Aljamal, Y., Prabhakar, N., Saleem, H., and Farley, D. R. (2019). Can the perceived difficulty of a task enhance trainee performance? *J. Surg. Educ.* 76, e193–e198. doi: 10.1016/j.jsurg.2019.08.005

Alloway, T. P., Gathercole, S. E., Kirkwood, H., and Elliott, J. (2008). Evaluating the validity of the automated working memory assessment. *Educ. Psychol.* 28, 725–734. doi: 10.1080/01443410802243828

Barnett, L., Mazzoli, E., Hawkins, M., Lander, N., Lubans, D., Caldwell, S., et al. (2020). Development of a self-report scale to assess children's perceived physical literacy. *Phys. Educ. Sport Pedagog.* 27, 1–26. doi: 10.1080/17408989.2020.1849596

Bonnet, C. T., and Baudry, S. (2016). A functional synergistic model to explain postural control during precise visual tasks. *Gait Posture* 50, 120–125. doi: 10.1016/j.gaitpost.2016.08.030

Boraita, R. J., Ibort, E. G., Torres, J. M. D., and Alsina, D. A. (2020). Gender differences relating to lifestyle habits and health-related quality of life of adolescents. *Child Indic. Res.* 13, 1937–1951. doi: 10.1007/s12187-020-09728-6

Brilliant, A. N., Meehan, W. P. I., and Howell, D. R. (2021). Static and dynamic cognitive performance in youth and collegiate athletes with concussion. *Clin. J. Sport Med.* 31:442. doi: 10.1097/JSM.0000000000000779

Bustillo-Casero, P., Cebrian-Bou, S., Cruz-Montecinos, C., Pardo, A., and García-Massó, X. (2020). Effects of a dual-task intervention in postural control and cognitive performance in adolescents. *J. Mot. Behav.* 52, 187–195. doi: 10.1080/00222895.2019.1600467

Bustillo-Casero, P., Villarrasa-Sapiña, I., and García-Massó, X. (2017). Effects of dual task difficulty in motor and cognitive performance: differences between adults and adolescents. *Hum. Mov. Sci.* 55, 8–17. doi: 10.1016/j.humov.2017.07.004

Cairney, J., Dudley, D., Kwan, M., Bulten, R., and Kriellaars, D. (2019). Physical literacy, physical activity and health: toward an evidence-informed conceptual model. *Sports Med.* 49, 371–383. doi: 10.1007/s40279-019-01063-3

Cavallo, F., Dalmasso, P., Ottová-Jordan, V., Brooks, F., Mazur, J., Välimaa, R., et al. (2015). Trends in life satisfaction in European and north-American adolescents from 2002 to 2010 in over 30 countries. *Eur. J. Pub. Health* 25, 80–82. doi: 10.1093/eurpub/ckv014

Cooper, S. B., Bandelow, S., Nute, M. L., Dring, K. J., Stannard, R. L., Morris, J. G., et al. (2016). Sprint-based exercise and cognitive function in adolescents. *Prev. Med. Rep.* 4, 155–161. doi: 10.1016/j.pmedr.2016.06.004

Cornish, K., Fox, G., Fyfe, T., Koopmans, E., Pousette, A., and Pelletier, C. A. (2020). Understanding physical literacy in the context of health: a rapid scoping review. *BMC Public Health* 20:1569. doi: 10.1186/s12889-020-09583-8

Corr, M., McSharry, J., and Murtagh, E. M. (2019). Adolescent girls' perceptions of physical activity: a systematic review of qualitative studies. *Am. J. Health Promot.* 33, 806–819. doi: 10.1177/0890117118818747

Diamond, A. (2013). Executive functions. *Annu. Rev. Psychol.* 64, 135–168. doi: 10.1146/annurev-psych-113011-143750

Edwards, L. C., Bryant, A. S., Keegan, R. J., Morgan, K., Cooper, S.-M., and Jones, A. M. (2018). 'Measuring' physical literacy and related constructs: a systematic review of empirical findings. *Sports Med.* 48, 659–682. doi: 10.1007/s40279-017-0817-9

Estevan, I., Gandia, S., Villarrasa-Sapiña, I., Bermejo, J. L., and García-Massó, X. (2018). Working memory task influence in postural stability and cognitive function in adolescents. *Mot. Control.* 22, 425–435. doi: 10.1123/mc.2017-0063

Estevan, I., García-Massó, X., Menescardi, C., Ortega-Benavent, N., Montalt-García, S., Romero-Martínez, J., et al. (2023). A classroom-based intervention to promote physical literacy in children: ALPHYL study protocol. *Behav. Sci.* 13:609. doi: 10.3390/bs13070609

Flanagan, D. P., Alfonso, V. C., Mascolo, J. T., and Hale, J. B. (2011). "The Wechsler intelligence scale for children, fourth edition in neuropsychological practice" in *Handbook of Pediatric Neuropsychology.* ed. A. S. Davis (New York, NY, US: Springer Publishing Company), 397–414.

Goldhammer, F., Naumann, J., Stelter, A., Tóth, K., Rölke, H., and Klieme, E. (2014). The time on task effect in reading and problem solving is moderated by task difficulty and skill: insights from a computer-based large-scale assessment. *J. Educ. Psychol.* 106, 608–626. doi: 10.1037/a0034716

Honrubia Montesinos, C., Gil Madrona, P., Losada Puente, L., Brian, A., and Saraiva, L. (2023). The relationship between early childhood teachers' professional development in physical education and Children's fundamental movement skills. *Early Educ. Dev.* 10, 1–14. doi: 10.1080/10409289.2023.2221766

Howell, D. R., Osternig, L. R., and Chou, L.-S. (2016). Consistency and cost of dual-task gait balance measure in healthy adolescents and young adults. *Gait Posture* 49, 176–180. doi: 10.1016/j.gaitpost.2016.07.008

Hulteen, R. M., Barnett, L. M., True, L., Lander, N. J., Del Pozo Cruz, B., and Lonsdale, C. (2020). Validity and reliability evidence for motor competence assessments in children and adolescents: a systematic review. *J. Sports Sci.* 38, 1717–1798. doi: 10.1080/02640414.2020.1756674

Kallio, J., Hakonen, H., Syväoja, H., Kulmala, J., Kankaanpää, A., Ekelund, U., et al. (2020). Changes in physical activity and sedentary time during adolescence: gender differences during weekdays and weekend days. *Scand. J. Med. Sci. Sports* 30, 1265–1275. doi: 10.1111/sms.13668

Kessels, R. P. C., van Zandvoort, M. J. E., Postma, A., Kappelle, L. J., and de Haan, E. H. F. (2000). The Corsi block-tapping task: standardization and normative data. *Appl. Neuropsychol.* 7, 252–258. doi: 10.1207/S15324826AN0704_8

Lacour, M., Bernard-Demanze, L., and Dumitrescu, M. (2008). Posture control, aging, and attention resources: models and posture-analysis methods. *Clin. Neurophysiol.* 38, 411–421. doi: 10.1016/j.neucli.2008.09.005

Li, W., Lee, A., and Solmon, M. (2007). The role of perceptions of task difficulty in relation to self-perceptions of ability, intrinsic value, attainment value, and performance. *Eur. Phys. Educ. Rev.* 13, 301–318. doi: 10.1177/1356336X07081797

Longmuir, P. E., Boyer, C., Lloyd, M., Borghese, M. M., Knight, E., Saunders, T. J., et al. (2017). Canadian agility and movement skill assessment (CAMSA): validity, objectivity, and reliability evidence for children 8–12 years of age. *J. Sport Health Sci.* 6, 231–240. doi: 10.1016/j.jshs.2015.11.004

Longmuir, P. E., Boyer, C., Lloyd, M., Yang, Y., Boiarskaia, E., Zhu, W., et al. (2015). The Canadian assessment of physical literacy: methods for children in grades 4 to 6 (8 to 12 years). *BMC Public Health* 15:767. doi: 10.1186/s12889-015-2106-6

Madehkhaksar, F., and Egges, A. (2016). Effect of dual task type on gait and dynamic stability during stair negotiation at different inclinations. *Gait Posture* 43, 114–119. doi: 10.1016/j.gaitpost.2015.09.009

Marco Ahulló, A., Fernández Baños, R., Monfort Torres, G., Bustillo Casero, P., Bermejo Ruiz, J.L., and García Massó, X. (2022). Dual task interference in children from 8 to 12 years old. Nuevas tendencias en educación física, deporte y recreación, Retos. 74–80.

Menescardi, C., Villarrasa-Sapiña, I., Lander, N., and Estevan, I. (2022). Canadian agility movement skill assessment (CAMSA) in a Spanish context: evidences of reliability and validity. *Meas. Phys. Educ. Exerc. Sci.* 26, 245–255. doi: 10.1080/1091367X.2021.2020794

Mueller, S. T., and Piper, B. J. (2014). The psychology experiment building language (PEBL) and PEBL test battery. *J. Neurosci. Methods* 222, 250–259. doi: 10.1016/j.jneumeth.2013.10.024

Oliver, E., Vallés-Pérez, I., Baños, R.-M., Cebolla, A., Botella, C., and Soria-Olivas, E. (2018). Visual data mining with self-organizing maps for "self-monitoring" data analysis. *Sociol. Methods Res.* 47, 492–506. doi: 10.1177/0049124116661576

Olivier, I., Cuisinier, R., Vaugoyeau, M., Nougier, V., and Assaiante, C. (2010). Age-related differences in cognitive and postural dual-task performance. *Gait Posture* 32, 494–499. doi: 10.1016/j.gaitpost.2010.07.008

Palluel, E., Nougier, V., and Olivier, I. (2010). Postural control and attentional demand during adolescence. *Brain Res.* 1358, 151–159. doi: 10.1016/j.brainres.2010.08.051

Pellicer-Chenoll, M., Garcia-Massó, X., Morales, J., Serra-Añó, P., Solana-Tramunt, M., González, L.-M., et al. (2015). Physical activity, physical fitness and academic achievement in adolescents: a self-organizing maps approach. *Health Educ. Res.* 30, 436–448. doi: 10.1093/her/cyv016

Pontifex, M. B., McGowan, A. L., Chandler, M. C., Gwizdala, K. L., Parks, A. C., Fenn, K., et al. (2019). A primer on investigating the after effects of acute bouts of physical activity on cognition. *Psychol. Sport Exerc.* 40, 1–22. doi: 10.1016/j.psychsport.2018.08.015

Ramos-Nuñez, A. I., Fischer-Baum, S., Martin, R. C., Yue, Q., Ye, F., and Deem, M. W. (2017). Static and dynamic measures of human brain connectivity predict complementary aspects of human cognitive performance. *Front. Hum. Neurosci.* 11:420. doi: 10.3389/fnhum.2017.00420

Robinson, D. B., and Randall, L. (2017). Marking physical literacy or missing the mark on physical literacy? A conceptual critique of Canada's physical literacy assessment instruments. *Meas. Phys. Educ. Exerc. Sci.* 21, 40–55. doi: 10.1080/1091367X.2016.1249793

Rodríguez-Guerrero, Y. I., Gil-Madrona, P., Pilar León, M., and Vásquez-Cruz, A. E. (2023). Relationship between fine/gross motor skills and language and math development in Colombian Caribbean children: a study in Barranquilla. *Infant Child Dev.* 32:e2430. doi: 10.1002/icd.2430

Sabiston, C. M., Pila, E., Vani, M., and Thogersen-Ntoumani, C. (2019). Body image, physical activity, and sport: a scoping review. Psychology of sport and exercise, 50 years of FEPSAC. *Curr. Future Direct. Sport Exerc. Psychol. Res.* 42, 48–57. doi: 10.1016/j.psychsport.2018.12.010

Schaefer, S. (2014). The ecological approach to cognitive–motor dual-tasking: findings on the effects of expertise and age. *Front. Psychol.* 5:1167. doi: 10.3389/fpsyg.2014.01167

Schaefer, S., Krampe, R. T., Lindenberger, U., and Baltes, P. B. (2008). Age differences between children and young adults in the dynamics of dual-task prioritization: body (balance) versus mind (memory). *Dev. Psychol.* 44, 747–757. doi: 10.1037/0012-1649.44.3.747

Seidler, R. D. (2004). Multiple motor learning experiences enhance motor adaptability. *J. Cogn. Neurosci.* 16, 65–73. doi: 10.1162/089892904322755566

Shin, J., and Grant, A. M. (2019). Bored by interest: how intrinsic motivation in one task can reduce performance on other tasks. *AMJ* 62, 415–436. doi: 10.5465/amj.2017.0735

Vesanto, J., Himberg, J., Alhoniemi, E., and Parhankangas, J. (1999). "Self-organizing map in Matlab: the SOM toolbox" in *Matlab DSP Conference*. Espoo, Finland, November 16–17, 35–40.

Wechsler, D. (1949). *Wechsler Intelligence Scale for Children*. San Antonio, TX, US: Psychological Corporation

Whitehead, M. (2001). The concept of physical literacy. *Eur. J. Phys. Educ.* 6, 127–138. doi: 10.1080/1740898010060205

Whitehead, M. (2019). *Physical Literacy Across the World*. London: Routledge.

Wollesen, B., Voelcker-Rehage, C., Regenbrecht, T., and Mattes, K. (2016). Influence of a visual-verbal Stroop test on standing and walking performance of older adults. *Neuroscience* 318, 166–177. doi: 10.1016/j.neuroscience.2016.01.031

Yang, J. (2015). The influence of motor expertise on the brain activity of motor task performance: a meta-analysis of functional magnetic resonance imaging studies. *Cogn. Affect. Behav. Neurosci.* 15, 381–394. doi: 10.3758/s13415-014-0329-0

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 11 January 2024
DOI 10.3389/fpsyg.2023.1338265

Check for updates

OPEN ACCESS

EDITED BY
Sabine Schaefer,
Saarland University, Germany

REVIEWED BY
Jennifer Lehmann,
University of Regensburg, Germany
Alberto Cordova,
University of Texas at San Antonio,
United States

*CORRESPONDENCE
Samiha Amara
✉ s.makaouer@squ.edu.om

RECEIVED 15 November 2023
ACCEPTED 22 December 2023
PUBLISHED 11 January 2024

CITATION
Amara S, Al-Hadabi B, El-Ashkar H, Gmada N, Habacha H and Mkaouer B (2024) Effect of dynamic balance on human mental rotation task in female badminton vs. volleyball players.
Front. Psychol. 14:1338265.
doi: 10.3389/fpsyg.2023.1338265

Effect of dynamic balance on human mental rotation task in female badminton vs. volleyball players

Samiha Amara[1,2]*, Badria Al-Hadabi[1], Heba El-Ashkar[1,3], Nabil Gmada[1,4], Hamdi Habacha[2,5] and Bessem Mkaouer[2]

[1]Physical Education and Sport Sciences Department, College of Education, Sultan Qaboos University, Muscat, Oman, [2]Department of Individual Sports, Higher Institute of Sport and Physical Education of Ksar Said, Manouba University, Tunis, Tunisia, [3]Department of Water Sports Training, Faculty of Physical Education for Girls, Helwan University, Helwan, Egypt, [4]Department of Biological Sciences, Higher Institute of Sport and Physical Education of Kef, University of Jendouba, El Kef, Tunisia, [5]Integrative Neuroscience and Cognition Center, Université de Paris, CNRS, Paris, France

Background: The present study aims to compare the mental rotation performance between two non-contact sports (i.e., badminton and volleyball) in different upright conditions (i.e., with and without dynamic balance).

Methods: Thirty-five female sports and physical education students voluntarily participated in the experiment, including fourteen specialists in badminton and twenty-one specialists in volleyball. The experiment involved a mental body rotation task with or without balance exercises on a wobble board.

Results: Badminton players outperformed volleyball players in the mental rotation tasks regardless of balance. More interestingly, the results revealed an overall decrease in reaction times when participants performed balance exercises simultaneously with mental rotation.

Discussion: Our findings suggest that introducing dynamic balance on a wobble board has immediate beneficial effects on the mental rotation performance of female badminton and volleyball players. These findings are discussed in the context of sport specificities and cognitive processing framework.

KEYWORDS

mental rotation, response time, dynamic balance, badminton, volleyball

1 Introduction

Brain imaging studies provide strong evidence for the involvement of the body's mirror system in observing complex movements (Calvo-Merino et al., 2005). Guillot and Collet (2005) showed that imagining a movement seems to preserve the spatial and temporal characteristics and be based on the same cognitive and neural systems as the actual movement. In a mental rotation task (MR), participants are asked to identify as fast as possible whether two misoriented images represent the same or mirrored object. Such object-based mental rotation tasks classically tap on visual processes, implying a linear increase in decision times as a function of the angular disparity between the two images (Shepard and Metzler, 1971). Later, some authors used images of body parts (i.e., hand or foot) in MR tasks and asked participants to judge whether the image depicted a right or left body part (i.e., laterality judgment). The results revealed that reaction times were affected by the biomechanical constraints of the real body parts movements (Sekiyama, 1982). These findings suggest that participants imagine their own body parts moving until alignment with the position of the stimulus (Moreau, 2012, 2013). Similarly, studies using depictions of human bodies with one arm outstretched revealed that the time to judge which arm is outstretched (i.e., laterality judgment) is dramatically affected by extreme (i.e., upside-down) body positions (Steggemann et al., 2011). Hence, these egocentric mental rotation tasks seem to imply embodied motor strategies transforming participants' own mental body representations to solve the task (Steggemann et al., 2011; Habacha et al., 2022; Khalfallah et al., 2022). That is, egocentric mental rotation involves cognitive processes used for both motor imagery and motor execution (Kawasaki and Higuchi, 2013).

Sport practice is an ideal context to develop spatial capacities, in particular visualization, orientation, and MR (Calvo-Merino et al., 2005; Pietsch and Jansen, 2012). During sports practice, the cognitive mechanisms underlying a movement play a key role in its improvement, considering the functional equivalence between actual and imagined skills (Decety, 2002). Moreau et al. (2012) and Pietsch and Jansen (2012) demonstrated large effects of motor training on mental rotation performance.

Additionally, athletes with different abilities in different sports appear to use different strategies to solve the same mental rotation tasks. Accordingly, the specific sensorimotor experiences seem to shape the cognitive processing during these tasks (Steggemann et al., 2011; Habacha et al., 2017, 2022). These findings support the involvement of motor processes in MR (Jansen and Lehmann, 2013) and further refine the established equivalence between actual and covert movement.

Furthermore, it has been shown that physical activity, especially a balance training program, improves memory and spatial awareness (Rogge et al., 2017). Rogge et al. (2017) compared the balance and cardiorespiratory fitness of two groups with and without 12 weeks of balance training. Only participants who followed the training significantly improved their balance, memory, and spatial awareness. The researchers explain that stimulation of the vestibular system during balance training could have induced changes in the hippocampus and parietal cortex, possibly through direct pathways between the vestibular system and these brain regions (Rogge et al., 2017). Bigelow and Agrawal (2015) showed a link between vestibular function and cognitive domains of visuospatial ability, including spatial memory, navigation, MR, and mental representation of three-dimensional space. Hofmann and Jansen (2021) investigated the relationship between MR and postural stability by examining the effects of performing an egocentric (i.e., bodily stimuli) and object-based (i.e., abstract stimuli) MR task simultaneously with stabilized postural sway in a tense position with both legs on a stable surface (i.e., a force plate). Their results showed that the egocentric task involved more body swaying than the object-based task. These results suggest that the egocentric mental rotation task involved more kinaesthetic imagery and motor processes in that subjects had to imagine rotating their own bodies' mental representations (Kessler and Rutherford, 2010), whereas the object-based task involves mostly visual processes that are not affected by the kinaesthetic body representations (Hofmann and Jansen, 2021). Furthermore, increasing the rotation angle of the stimuli in the MR task resulted in more body sway (Hofmann et al., 2022), confirming the involvement of motor processes. Pellecchia (2003) corroborated this finding by revealing that more body sway may be due to increased difficulty of concurrent cognitive tasks. In addition, attentional focus (i.e., internal and external) is very important. Mental body rotation combined with dynamic balance engages both external and internal attentional focus, noting that the performance benefits are greatest when participants use an external focus of attention (e.g., directed attention on the effect of movement on the environment) versus an internal focus of attention (e.g., a focus on body movement) (Wulf et al., 1999, 2010; Singh and Wulf, 2022).

However, not all athletes automatically engage motor processes during MR of bodily stimuli, resulting in contradictory results. Participation in certain sports, such as wrestling, seems to favor motor-based strategies to outperform other athletes or non-athletes, even if abstract objects are used in MR (Moreau et al., 2012; Pietsch et al., 2019). Furthermore, athletes whose sports require more visuospatial and kinaesthetic abilities linked to real body rotations, such as wrestlers and gymnasts, show better performance in MR of bodily stimuli than athletes who practice cardiovascular activities such as running (Moreau et al., 2012; Schmidt et al., 2016). In contrast, team sports encourage the use of visual strategies, as athletes are trained to perceive and analyze moving objects and examine spatial relationships with partners and opponents from off-centre perspectives (Steggemann et al., 2011).

Moreover, athletes from team sports and racquet sports showed significantly shorter reaction times (i.e., go/no-go) than those in other sports (Dogan, 2009; Erickson, 2020). Delpont et al. (1991) observed faster transmission in the visual pathway in tennis and squash players compared to rowers and non-athlete controls. That is, team sports and racquet sports, which require rapid visual activity, seem to enhance the development of information processing and mental rotational performance. However, other studies have shown that elite team athletes do not exhibit better mental rotational performance of bodily and abstract figures compared to non-athletes (Jansen et al., 2012; Heppe et al., 2016).

One way to provide new insight into these contradictory results is to compare the performance of badminton and volleyball female players in MR of bodily stimuli in different upright conditions (i.e., with and without dynamic balance). The effect of balance on MR performance in one group and not the other would help understand the processes engaged in the task.

We hypothesized that the dynamic balance condition would have immediate beneficial effects on the MR task, resulting in decreased response times for both female badminton and volleyball players. Additionally, we made the hypothesis that female badminton players would be more effectively able and faster than their volleyball counterparts to recognize the correct response of rotated body images, given that the shuttlecock in badminton travels at a much faster and less predictable trajectory than the ball in volleyball.

2 Methods

2.1 Participants

A minimum sample size of 35 participants was determined from an *a priori* statistical power analysis using G*Power software [Version 3.1,

FIGURE 1
Example of stimulus of objected-based body condition.

University of Dusseldorf, Germany (Faul et al., 2009)]. The power analysis was computed with an assumed power of 0.95 at an alpha level of 0.05 and a moderate effect size of 0.30. Therefore, thirty-five volunteer female sports and physical education students, fourteen specialists in badminton (age 20.48 ± 1.04 years; height 1.80 ± 0.03 m; weight 78.12 ± 3.73 kg) and twenty-one specialists in volleyball (age 21.57 ± 1.47 years; height 1.87 ± 0.02 m; weight 80.03 ± 4.03 kg) agreed to participate in this study. After being informed in advance of the procedures, methods, benefits, and possible risks of the study, each participant reviewed and signed a consent form to participate in the study. The experimental protocol was performed in accordance with the Declaration of Helsinki for human experimentation (Carlson et al., 2004) and was approved by the University Local Ethical Committee (EDU/PHEDS83961/2022).

2.2 Experimental design and procedures

This study consists of three random assessments (i.e., randomized counterbalanced, Latin Square), every assessment took place on a separate successive day. All assessments were carried out in the gymnasium at the same time of the day (between 10:00 PM and 12:00 PM). Each of the assessments was a human mental rotation task with and/or without balance exercises, i.e., (frontal and/or sagittal balance) on a wobble board SPBB [length and width 420 mm × 420 mm; height 70 mm (Mattacola and Lloyd, 1997)].

Five stimuli were used in the mental rotation task with egocentric transformation (ET), each including a pair of standard and comparison images (Figure 1). We used the standard image on the left part of the monitor screen and the rotated image on the right of the screen. The standard image consists of an upright human figure with either the left or right arm outstretched. The comparison image was either a copy or a mirror-reversed copy of the standard one, rotated in one of five orientations (45°, 135°, 180°, 225°, and 315°).

The mental rotation task was performed in three conditions:

a. In a standing position: The subject takes an upright position in front of the PC with a wireless joystick in his hand.

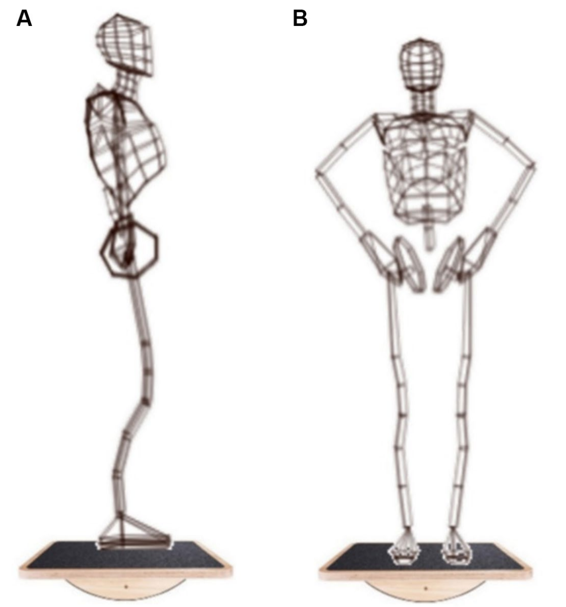


FIGURE 2
Experimental protocol: **(A)** Bipedal sway, sagittal balance; **(B)** Bipedal sway, frontal balance (El-Ashkar et al., 2023).

b. In sagittal balance: The subject takes an upright position on a Single Plane Balance Board (SPBB) in front of the PC with a wireless joystick in his hand (Figure 2A).
c. In frontal balance: The subject takes an upright position on a Single Plane Balance Board (SPBB) in front of the PC with a wireless joystick in his hand (Figure 2B).

This results in a total of 60 trials: 3 (conditions: static, sagittal and frontal balance) × 2 (groups: badminton and volleyball) × 5 (angle display: 45°, 135°, 180°, 225°, and 315°) × 2 (same or different). The order of stimulus presentation was counterbalanced, and each rotation angle could not appear 2 times in succession.

10.3389/fpsyg.2023.1338265

TABLE 1 ANOVA with repeated measures.

Source		df	Mean square	*F*	Sig.	Effect size	Power
Balance	RT Gen	2	3175776.700	15.115	0.000**	1.754	0.999
	EP Gen	2	47.657	1.180	0.314	0.380	0.250
	RT 45°	2	1711623.410	7.018	0.002**	1.353	0.917
	EP 45°	2	124.813	2.548	0.086	0.557	0.493
	RT 90°	2	2541526.356	8.211	0.001**	1.235	0.953
	EP 90°	2	21.084	0.239	0.788	0.167	0.086
	RT 135°	2	4090458.058	13.037	0.000**	1.256	0.996
	EP 135°	2	503.038	2.107	0.130	0.505	0.418
	RT 180°	2	5474120.555	12.349	0.000**	1.222	0.995
	EP 180°	2	324.304	1.093	0.341	0.363	0.234
	RT 225°	2	6258626.916	10.216	0.000**	1.111	0.983
	EP 225°	2	92.726	0.490	0.615	0.246	0.127
	RT 270°	2	1746830.048	4.253	0.018*	0.717	0.725
	EP 270°	2	71.822	0.674	0.513	0.285	0.159
	RT 315°	2	9182409.417	32.906	0.000**	1.996	1.000
	EP 315°	2	710.680	4.420	0.016*	0.731	0.742
Sports	RT Gen	1	1495019.892	4.170	0.048*	0.716	0.539
	EP Gen	1	1842.046	3.924	0.050*	0.698	0.503
	RT 45°	1	1625891.593	2.829	0.102	0.585	0.372
	EP 45°	1	540.043	1.522	0.226	0.429	0.224
	RT 90°	1	649695.123	1.120	0.298	0.369	0.177
	EP 90°	1	754.204	1.787	0.190	0.463	0.255
	RT 135°	1	20097.730	0.027	0.870	0.063	0.053
	EP 135°	1	2546.911	3.549	0.068	0.655	0.448
	RT 180°	1	72024.306	0.055	0.815	0.089	0.056
	EP 180°	1	5070.882	5.458	0.026*	0.813	0.621
	RT 225°	1	386098.537	0.251	0.620	0.179	0.078
	EP 225°	1	1477.890	1.702	0.201	0.454	0.245
	RT 270°	1	1620162.190	2.150	0.152	0.509	0.296
	EP 270°	1	2415.585	4.628	0.039*	0.749	0.551
	RT 315°	1	142798.030	0.246	0.623	0.007	0.167
	EP 315°	1	1333.900	4.174	0.049*	0.695	0.509
Balance * Sports	RT Gen	2	121424.870	5.530	0.018*	0.715	0.677
	EP Gen	2	1.317	0.033	0.968	0.063	0.055
	RT 45°	2	248845.956	1.020	0.366	0.351	0.221
	EP 45°	2	13.676	0.279	0.757	0.179	0.092
	RT 90°	2	204010.169	0.659	0.521	0.285	0.156
	EP 90°	2	59.082	0.670	0.515	0.285	0.158
	RT 135°	2	236124.603	0.753	0.475	0.300	0.173
	EP 135°	2	124.774	0.523	0.595	0.255	0.133
	RT 180°	2	152109.886	0.343	0.711	0.201	0.103
	EP 180°	2	60.048	0.202	0.817	0.155	0.080
	RT 225°	2	50449.177	0.082	0.921	0.089	0.062
	EP 225°	2	77.672	0.410	0.665	0.220	0.114

(Continued)

TABLE 1 (Continued)

Source		df	Mean square	F	Sig.	Effect size	Power
	RT 270°	2	81556.607	0.199	0.820	0.155	0.080
	EP 270°	2	34.887	0.328	0.722	0.201	0.100
	RT 315°	2	175709.665	0.630	0.536	0.278	0.151
	EP 315°	2	7.053	0.044	0.957	0.063	0.056

RT, Response time; EP, Error percentage; Gen, General; *Significant at $p < 0.05$; **Significant at $p < 0.001$.

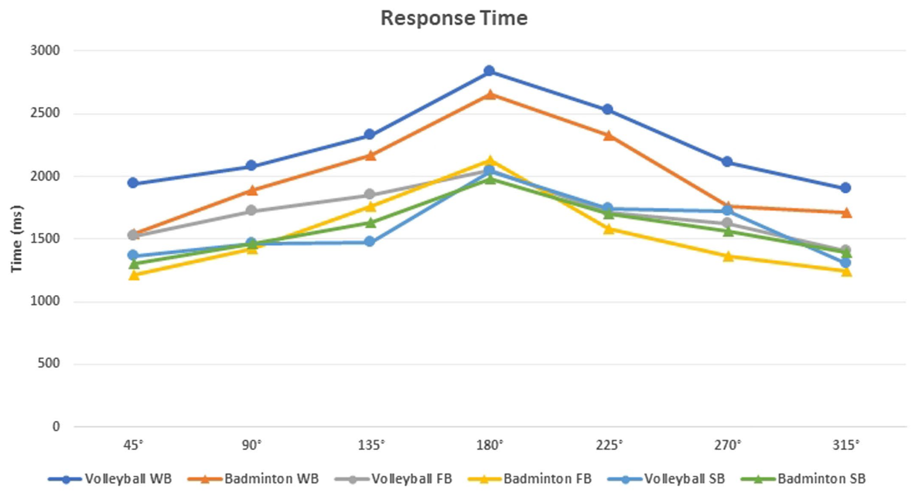


FIGURE 3
Response time for all body rotation angles and conditions.

Each trial began with a blank screen for 1,000 ms, after which a black fixation cross was displayed at the centre for 500 ms. After fixation, the test image was presented for a maximum of 5,000 ms and remained on the screen until a response was given. Stimuli were displayed, and response times were recorded via the free software OpenSesame (Mathôt et al., 2012). The mental rotation task lasted about 4 min.

2.3 Statistical analysis

The SPSS 20 package [SPSS, Chicago, IL, USA] program was used for the data analysis. Descriptive statistics (i.e., means ± SD) were performed for all variables. The effect size was conducted using G*Power software [Version 3.1, University of Dusseldorf, Germany]. The following scale was used for the interpretation of d: <0.2, trivial; 0.2–0.6, small; 0.6–1.2, moderate; 1.2–2.0, large; and > 2.0, very large (Hopkins, 2002). The normality of distribution estimated by the Kolmogorov–Smirnov test was acceptable for all variables ($p > 0.05$). Consequently, ANOVA with repeated measures on two factors (i.e., balance and group) was used to benchmark different balance strategies. The Bonferroni test was applied in post-hoc analysis for pairwise comparisons. Additionally, effect sizes (d) were determined from ANOVA output by converting the partial eta-squared to Cohen's d. *A priori* level less than or equal to 0.5% ($p \leq 0.05$) was used as a criterion for significance.

3 Results

The ANOVA showed a significant main effect of "balance" (i.e., without balance (WB), with sagittal (SB) and frontal balance (FB)) and "group" (i.e., badminton and volleyball) in the response time ($p < 0.01$) and the error percentage ($p < 0.05$). In addition, results revealed a significant interaction between "balance" and "group" [in general RT (Table 1)].

Pairwise comparison between balance conditions (i.e., without balance, with sagittal and frontal balance) showed significant differences ($p < 0.01$) for RT in all rotation degrees (i.e., 45°, 90°, 135°, 180°, 225°, 270°, and 315°) between WB and FB conditions. Also, between WB and SB conditions. In addition, there is a significant RT difference ($p < 0.01$) between FB and SB only in 135° rotation. Then, the EP results showed a significant difference ($p < 0.05$) in 315° body rotation angle, in WB vs. FB conditions (6.19 ± 13.45% and 3.47 ± 8.15% respectively) and FB vs. SB conditions (3.47 ± 8.15% and 5.23 ± 9.71% respectively) (Figure 3; Table 2).

Furthermore, between-group comparison (i.e., badminton vs. volleyball), showed a significant difference ($p < 0.05$) in the general RT (1644.91 ± 465.02 ms vs. 2182.08 ± 684.24 ms respectively) and general EP (2.89 ± 3.11% vs. 11.22 ± 16.63% respectively). Also, in the EP at 180°, 270° and 315° body rotation angle in WB (180° = 3.57 ± 7.10% vs. 19.05 ± 24.88%, 270° = 1.19 ± 4.46 vs. 12.70 ± 18.18% and 315° = 1.20 ± 4.44 vs. 9.52 ± 18.30% respectively), FB (180° = 7.17 ± 14.21% vs. 23.14 ± 29.51% and 270° = 2.38 ± 6.05 vs.

TABLE 2 Pairwise comparison.

Measure		Mean diff	Std. error	Sig.	Effect size
RT Gen	WB vs. FB	505.871	123.914	0.000**	4.082
	WB vs. SB	555.627	125.253	0.000**	4.346
	BB vs. AB	49.756	80.473	0.541	0.618
RT 45°	WB vs. FB	370.229	127.237	0.006**	2.910
	WB vs. SB	408.769	143.842	0.008**	2.841
	FB vs. SB	38.539	81.677	0.640	0.471
RT 90°	WB vs. FB	412.583	152.637	0.011*	2.703
	WB vs. SB	521.337	152.319	0.002**	3.421
	FB vs. SB	108.753	93.654	0.254	1.161
RT 135°	WB vs. FB	438.344	158.909	0.009**	2.758
	WB vs. SB	689.396	150.210	0.000**	4.589
	FB vs. SB	251.052	90.617	0.009**	2.770
RT 180°	WB vs. FB	655.749	172.691	0.001**	3.797
	WB vs. SB	735.619	166.801	0.000**	4.431
	FB vs. SB	79.870	146.669	0.590	0.541
RT 225°	WB vs. FB	784.572	242.246	0.003**	3.242
	WB vs. SB	703.960	197.011	0.001**	3.753
	FB vs. SB	80.612	109.077	0.465	0.733
RT 270°	WB vs. FB	448.896	152.259	0.006**	2.953
	WB vs. SB	293.990	150.947	0.060	1.953
	FB vs. SB	154.906	165.470	0.356	0.933
RT 315°	WB vs. FB	916.910	143.518	0.000**	6.411
	WB vs. SB	893.558	139.367	0.000**	6.428
	FB vs. SB	23.352	99.047	0.815	0.232
EP 315°	WB vs. FB	7.539	3.479	0.038*	2.513
	WB vs. SB	0.794	1.568	0.616	0.012
	FB vs. SB	8.333	3.762	0.034*	2.777

RT, Response time; EP, Error percentage; Gen, General; WB, without balance; FB, Frontal balance; SB, Sagittal balance; *Significant at $p < 0.05$; **Significant at $p < 0.001$.

12.71 ± 18.41% respectively) and SB (315° = 1.18 ± 4.44 vs. 7.93 ± 11.32% respectively) conditions.

Regarding the balance * group interaction, there is a significant difference ($p < 0.05$) in the general RT between badminton and volleyball players, particularly in WB condition (1644.91 ± 465.02 ms vs. 2182.07 ± 24.09 ms respectively). When introducing the FB or SB task, the RTs are very close (1518.42 ± 405.40 ms vs. 1701.58 ± 554.86 ms and 1555.41 ± 372.47 ms vs. 1565.08 ± 433.56 ms respectively, badminton and volleyball players).

On the other side, balance (i.e., velocity and displacement) was enhanced when introducing MR task ($p < 0.01$) in both sports disciplines (i.e., volleyball and badminton) and balance conditions (i.e., FB and SB) (Figures 4, 5). In addition, there is a significant interaction between FB and sports in the displacement [$F_{(1,33)} = 4.333$; $p < 0.05$; $d = 0.876$] in favor of badminton players (10.886 ± 4.029 cm vs. 8.053 ± 3.172 cm, $p < 0.001$, $d = 1.256$, respectively volleyball and badminton players).

4 Discussion

This study aimed to compare the MR performance between two non-contact sports, namely badminton and volleyball, across different upright conditions (i.e., with and without dynamic balance) in female players. More specifically, the aim was to examine whether dynamic balance affect the performance of these female athletes implying their use of motor processes during the task.

Our results showed a significant decrease of RT in both balance conditions (FB and SB) compared to the static condition (WB). This finding suggests that the unstable equilibrium position could have enhanced the cognitive processing of participants allowing them to perform the MR task faster. In this context (Kawasaki et al., 2014), showed that participants in unipedal standing performed the MR task faster than the bipedal standing group and had lower sway scores. They revealed that the MR is involved in controlling upright human posture and could be related to the ability to stand as still as possible. Taken together with our results, these findings suggest that the ability to mentally imagine body movements may be related to postural stability while involving a challenging postural task. Thus, our results are consistent with those of Kawasaki and Higuchi (2013), which showed that MR interventions have immediate beneficial effects using dynamic balance conditions.

Additionally, the decrease of RT in balance conditions was significant in all body rotation angles, ranging from body orientations that every athlete could execute during practice to extreme body positions. That is, cognitive processing seems to be enhanced even with stimuli that require easy or little processing, highlighting the robustness of the effect of balance. Accordingly, our results confirm that a dual task (i.e., MR and body sway) enhances both performances (i.e., RT and stability) in FB and SB conditions (Hofmann and Jansen, 2021; Hofmann et al., 2022). In addition, Rogge et al. (2017) proved beneficial effects on memory, orientation, and spatial cognition after balance training through the activation of the vestibular system.

Furthermore, our results reveal a classic linear increase of RT as a function of rotation angle up to 180° and a decrease after. Habacha et al. (2022) and Steggemann et al. (2011) computed mean RT of angular disparities for which the shortest rotation path between stimulus and target is the same (e.g., 45°–315°, 90°–270°, 135°–225°). In addition, Parsons (1987) and Zartor et al. (2010) confirm that participants in mental body rotation tasks classically choose the shortest path to align their body representation with the stimuli. This interpretation can explain why the 180° angle represents the greatest difficulty in our study.

Keehner et al. (2006) and Michelon and Zacks (2006) revealed that the classical behavioral result for egocentric MR tasks implies an increase of RT for angles above 60° or 90°. Angles below 60° detect body positions that are similarly easy to physically and mentally adopt and thus show no increase in RT. In our study, the introduction of a second task (i.e., postural balance) could have made the easy positions difficult to adopt, since the balance affected the starting position of the body representation to transform. This is in line with the studies showing that the change in body position during MR can affect performance (Ionta et al., 2007; Ionta and Blanke, 2009). That is, more cognitive processing could have been required and thus RT increased even for small angles. Furthermore, Huxhold et al. (2006) and Shumway-Cook and Woollacott (2007) suggest that postural stability is the result of a shift of attention to the cognitive task and therefore

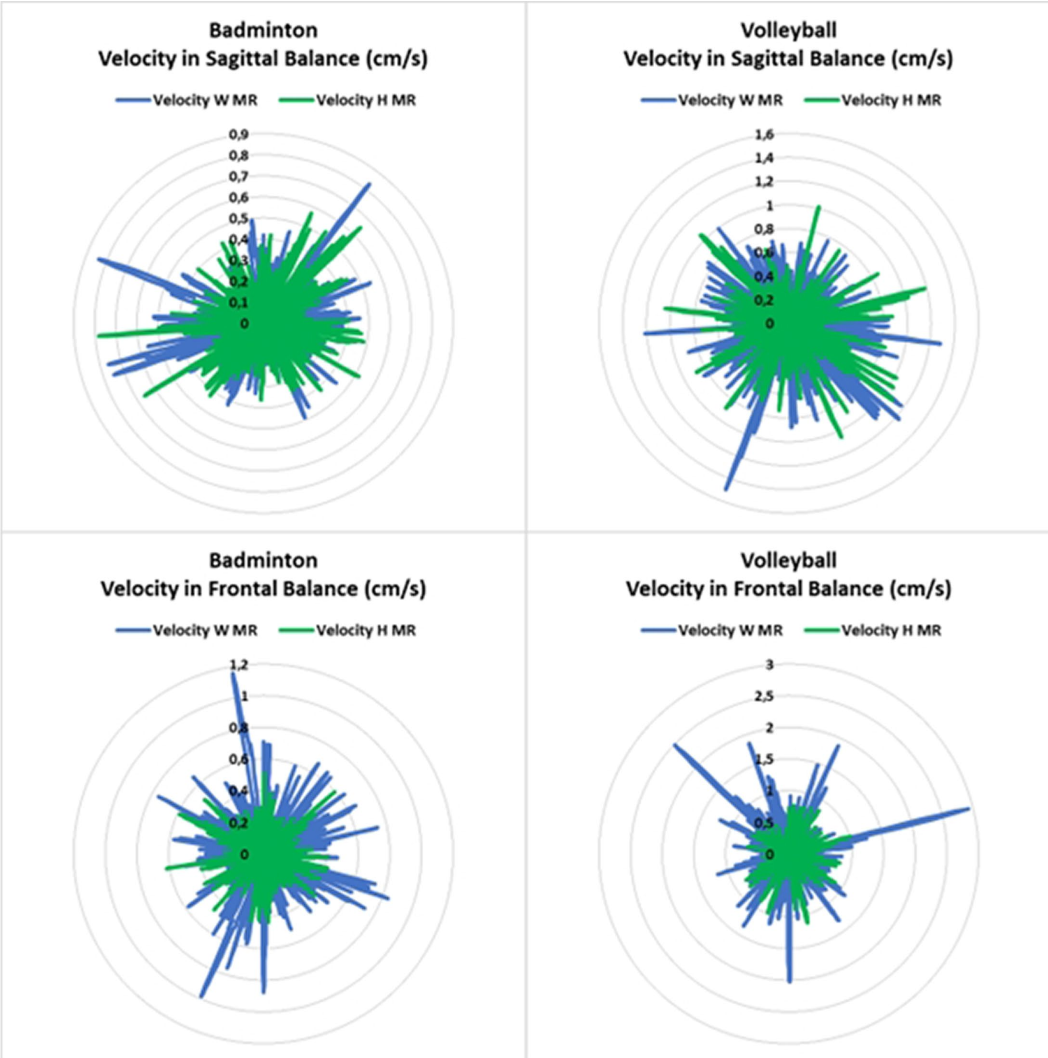


FIGURE 4
Balance velocity in frontal and sagittal conditions with and without human mental rotation task.

the automaticity and efficiency of the postural control processes are enhanced. Against this, Hofmann and Jansen (2021) revealed that in egocentric tasks, the angular disparity does not influence postural sway. For object-based tasks, there is a tendency for higher rotation angles to lead to more postural sway.

Our results revealed that female badminton players have faster RT and smaller error percentages than female volleyball players. This could be explained by the fact that, in badminton, the shuttlecock travels at a much higher speed and with a less predictable trajectory than a volleyball, requiring faster reflexes to be able to hit the shuttlecock accurately (Phomsoupha and Laffaye, 2015). Additionally, female badminton players often must react to shots that are hit directly at them, whereas female volleyball players have more time to react because the ball is hit back and forward across a net. Moreover, research studies have shown that badminton players tend to have faster reaction times compared to other athletes practicing other sports such as football, handball, volleyball, wrestling, and ice skating (Bańkosz et al., 2013; Dube et al., 2015). Consequently, Alexander and Boreskie (1989) classified sports such as badminton, table tennis, and squash (i.e., with racquets) as reaction sports.

Interestingly, the interaction between balance and groups was only significant in the WB condition. When introducing FB or SB tasks, the RTs were fairly similar. This suggests that both female groups react in the same way to stress/disturbance of postural balance on both the frontal and sagittal planes (Bisht et al., 2017). Bisht et al. (2017) showed no significant difference in balance ability between volleyball and badminton players and suggested that balance ability is equally necessary and a prerequisite for both of these sports. That is, badminton and volleyball players could similarly develop their balance skills during their practice, and a disturbance in their balance would thus induce almost the same reaction (Trivedi and Rawal, 2020).

5 Conclusion

In summary, introducing dynamic balance on a wobble board seems to have benefits on the performance of a concurrent mental rotation task, with similar benefits observed in both female badminton and volleyball players. Additionally, the superior performance of

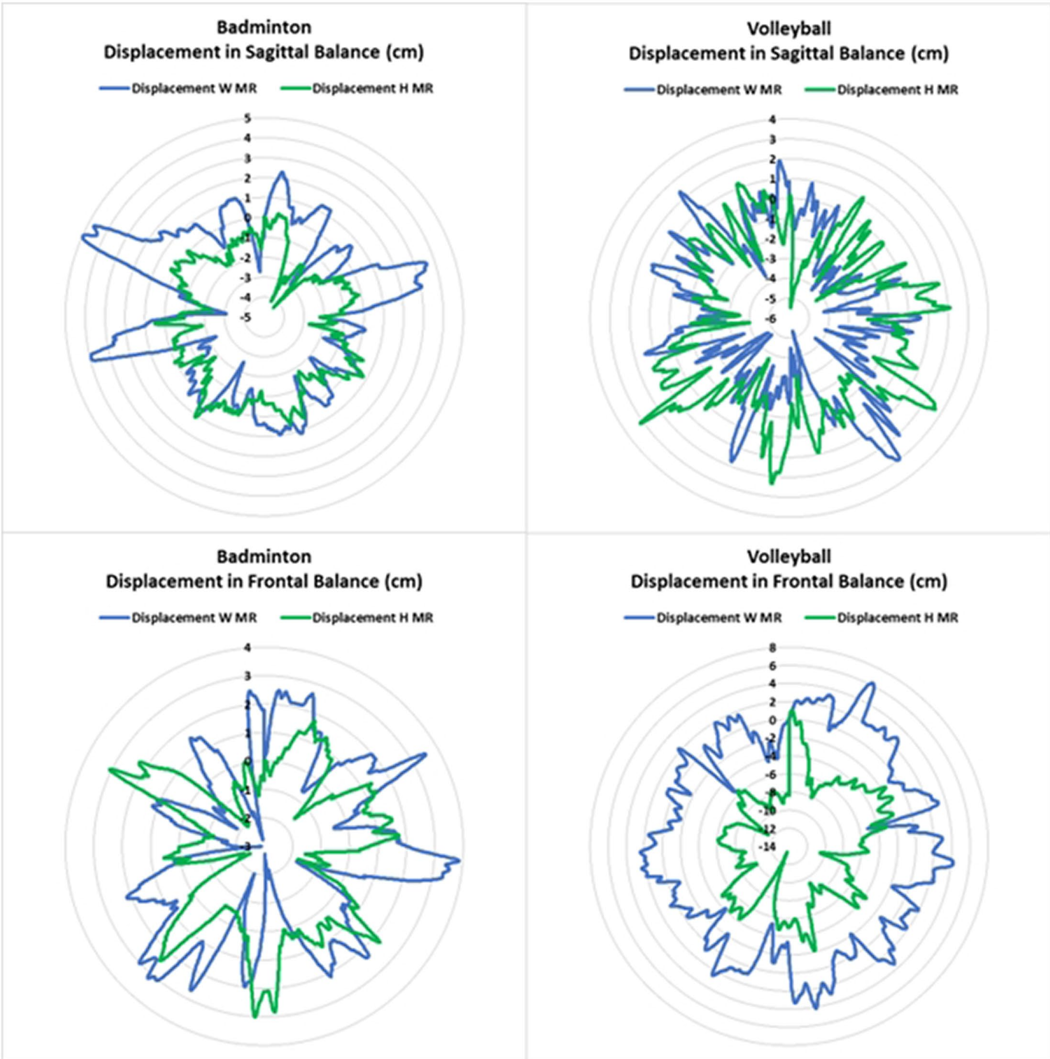


FIGURE 5
Balance displacement in frontal and sagittal conditions with and without human mental rotation task.

female badminton players compared to volleyball players suggests distinct effects of these two sports on mental rotation abilities. Furthermore, dynamic balance seems to be equally necessary and a prerequisite for both female badminton and volleyball players.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Sultan Qaboos Local Ethical Committee (EDU/PHEDS83961/2022). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

SA: Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Software, Writing – original draft, Writing – review & editing. BA-H: Funding acquisition, Investigation, Project administration, Resources, Writing – review & editing. HE-A: Investigation, Methodology, Project administration, Writing – review & editing. NG: Project administration, Resources, Supervision, Visualization, Writing – review & editing. HH: Conceptualization, Methodology, Validation, Writing – review & editing. BM: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Software, Supervision, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. The research reported in this paper was supported by the Physical Education and Sport Sciences Department, College of Education, Sultan Qaboos University.

Acknowledgments

We would like to thank all the participants who took part in this investigation. A particular thank you to the Physical Education and Sport Sciences Department, College of Education, Sultan Qaboos University.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Alexander, M. J. L., and Boreskie, S. L. (1989). An analysis of fitness and time-motion characteristics of handball. *Am. J. Sports Med.* 17, 76–82. doi: 10.1177/036354658901700113

Bańkosz, Z., Nawara, H., and Ociepa, M. (2013). Assessment of simple reaction time in badminton players. *TRENDS in Sport Sciences* 20, 54–61.

Bigelow, R. T., and Agrawal, Y. (2015). Vestibular involvement in cognition: visuospatial ability, attention, executive function, and memory. *J. Vestib. Res.* 25, 73–89. doi: 10.3233/VES-150544

Bisht, R., Singh, C. M., and Mardikar, M. (2017). A comparative study of reaction ability and balance ability among players belonging to contact, semi-contact and non-contact sports. *Int. J. Phys. Educat. Sports Health* 4, 77–80.

Calvo-Merino, B., Glaser, D. E., Grèzes, J., Passingham, R. E., and Haggard, P. (2005). Action observation and acquired motor skills: an FMRI study with expert dancers. *Cereb. Cortex* 15, 1243–1249. doi: 10.1093/cercor/bhi007

Carlson, R. V., Boyd, K. M., and Webb, D. J. (2004). The revision of the Declaration of Helsinki: past, present and future. *Br. J. Clin. Pharmacol.* 57, 695–713. doi: 10.1111/j.1365-2125.2004.02103.x

Decety, J. (2002). Naturaliser l'empathie. *L'Encéphale* 28, 9–20.

Delpont, E., Dolisi, C., Suisse, G., Bodino, G., and Gastaud, M. (1991). Visual evoked potentials: differences related to physical activity. *Int. J. Sports Med.* 12, 293–298. doi: 10.1055/s-2007-1024684

Dogan, B. (2009). Multiple-choice reaction and visual perception in female and male elite athletes. *J. Sports Med. Phys. Fitness* 49, 91–96.

Dube, S. P., Mungal, S. U., and Kulkarni, M. B. (2015). Simple visual reaction time in badminton players: a comparative study. *Natl. J. Physiol. Pharm. Pharmacol.* 5, 18–20. doi: 10.5455/njppp.2015.5.080720141

El-Ashkar, H. I. M., Amara, S., Al-Hadabi, B., and Mkaouer, B. (2023). Analysis of postural balance between two aquatic sports using vertical vs horizontal body position. *Eur. Rev. Med. Pharmacol. Sci.* 27, 836–844. doi: 10.26355/eurrev_202302_31175

Erickson, G. B. (2020). *Sports vision: vision care for the enhancement of sports performance*. St. Louis, Missouri: Elsevier Health Sciences.

Faul, F., Erdfelder, E., Buchner, A., and Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. *Behav. Res. Methods* 41, 1149–1160. doi: 10.3758/BRM.41.4.1149

Guillot, A., and Collet, C. (2005). Duration of mentally simulated movement: a review. *J. Mot. Behav.* 37, 10–20. doi: 10.3200/JMBR.37.1.10-20

Habacha, H., Lejeune-Poutrain, L., and Molinaro, C. (2017). Realistic stimuli reveal selective effects of motor expertise during a mental body rotation task. *Am. J. Psychol.* 130, 47–62. doi: 10.5406/amerjpsyc.130.1.0047

Habacha, H., Mallek, M., Moreau, D., Khalfallah, S., and Mkaouer, B. (2022). Differences in mental rotation strategies depend on the level of motor expertise. *Am. J. Psychol.* 135, 325–336. doi: 10.5406/19398298.135.3.06

Heppe, H., Kohler, A., Fleddermann, M.-T., and Zentgraf, K. (2016). The relationship between expertise in sports, visuospatial, and basic cognitive skills. *Front. Psychol.* 7:904. doi: 10.3389/fpsyg.2016.00904

Hofmann, P., and Jansen, P. (2021). The relation of mental rotation and postural stability. *J. Mot. Behav.* 55, 580–593. doi: 10.1080/00222895.2021.1899113

Hofmann, P., Jost, L., and Jansen, P. (2022). Embodied mental rotation – does it affect postural stability? *J. Mot. Behav.* 55, 202–219. doi: 10.1080/00222895.2022.2151970

Hopkins, W.G. (2002). A new view of statistics. A scale of magnitudes for effect statistics. Available at: www.sportsci.org/resource/stats/effectmag.html (Accessed February 12, 2021)

Huxhold, O., Li, S.-C., Schmiedek, F., and Lindenberger, U. (2006). Dual-tasking postural control: aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Res. Bull.* 69, 294–305. doi: 10.1016/j.brainresbull.2006.01.002

Ionta, S., and Blanke, O. (2009). Differential influence of hands posture on mental rotation of hands and feet in left and right handers. *Exp. Brain Res.* 195, 207–217. doi: 10.1007/s00221-009-1770-0

Ionta, S., Fourkas, A. D., Fiorio, M., and Aglioti, S. M. (2007). The influence of hands posture on mental rotation of hands and feet. *Exp. Brain Res.* 183, 1–7. doi: 10.1007/s00221-007-1020-2

Jansen, P., and Lehmann, J. (2013). Mental rotation performance in soccer players and gymnasts in an object-based mental rotation task. *Adv. Cogn. Psychol.* 9, 92–98. doi: 10.5709/acp-0135-8

Jansen, P., Lehmann, J., and Van Doren, J. (2012). Mental rotation performance in male soccer players. *PLoS One* 7:e48620. doi: 10.1371/journal.pone.0048620

Kawasaki, T., and Higuchi, T. (2013). Immediate beneficial effects of mental rotation using foot stimuli on upright postural stability in healthy participants. *Rehabil. Res. Pract.* 2013:890962, 1–7. doi: 10.1155/2013/890962

Kawasaki, T., Yasuda, K., Fukuhara, K., and Higuchi, T. (2014). Relationship between mental rotation of body parts and postural stability during quiet stance. *J. Imagery Res. Sport Phys. Activ.* 9, 39–46. doi: 10.1515/jirspa-2014-0001

Keehner, M., Guerin, S. A., Miller, M. B., Turk, D. J., and Hegarty, M. (2006). Modulation of neural activity by angle of rotation during imagined spatial transformations. *NeuroImage* 33, 391–398. doi: 10.1016/j.neuroimage.2006.06.043

Kessler, K., and Rutherford, H. (2010). The two forms of visuo-spatial perspective taking are differently embodied and subserve different spatial prepositions. *Front. Psychol.* 1:213. doi: 10.3389/fpsyg.2010.00213

Khalfallah, S., Mkaouer, B., Amara, S., Habacha, H., and Souissi, N. (2022). Effects of differing exercise intensities on the response time of gymnasts and nongymnasts in a mental body rotation task. *Am. J. Psychol.* 135, 69–76. doi: 10.5406/19398298.135.1.06

Mathôt, S., Schreij, D., and Theeuwes, J. (2012). OpenSesame: an open-source, graphical experiment builder for the social sciences. *Behav. Res. Methods* 44, 314–324. doi: 10.3758/s13428-011-0168-7

Mattacola, C. G., and Lloyd, J. W. (1997). Effects of a 6-week strength and proprioception training program on measures of dynamic balance: a single-case design. *J. Athl. Train.* 32, 127–135.

Michelon, P., and Zacks, J. M. (2006). Two kinds of visual perspective taking. *Percept. Psychophys.* 68, 327–337. doi: 10.3758/BF03193680

Moreau, D. (2012). The role of motor processes in three-dimensional mental rotation: shaping cognitive processing via sensorimotor experience. *Learn. Individ. Differ.* 22, 354–359. doi: 10.1016/j.lindif.2012.02.003

Moreau, D. (2013). Constraining movement alters the recruitment of motor processes in mental rotation. *Exp. Brain Res.* 224, 447–454. doi: 10.1007/s00221-012-3324-0

Moreau, D., Clerc, J., Mansy-Dannay, A., and Guerrien, A. (2012). Enhancing spatial ability through sport practice: evidence for an effect of motor training on mental rotation performance. *J. Individ. Differ.* 33, 83–88. doi: 10.1027/1614-0001/a000075

Parsons, L. M. (1987). Imagined spatial transformation of one's body. *J. Exp. Psychol. Gen.* 116, 172–191. doi: 10.1037/0096-3445.116.2.172

Pellecchia, G. L. (2003). Postural sway increases with attentional demands of concurrent cognitive task. *Gait Posture* 18, 29–34. doi: 10.1016/S0966-6362(02)00138-8

Phomsoupha, M., and Laffaye, G. (2015). The science of badminton: game characteristics, anthropometry, physiology, visual fitness and biomechanics. *Sports Med.* 45, 473–495. doi: 10.1007/s40279-014-0287-2

Pietsch, S., and Jansen, P. (2012). Different mental rotation performance in students of music, sport and education. *Learn. Individ. Differ.* 22, 159–163. doi: 10.1016/j.lindif.2011.11.012

Pietsch, S., Jansen, P., and Lehmann, J. (2019). The choice of sports affects mental rotation performance in adolescents. *Front. Neurosci.* 13:224. doi: 10.3389/fnins.2019.00224

Rogge, A.-K., Röder, B., Zech, A., Nagel, V., Hollander, K., Braumann, K.-M., et al. (2017). Balance training improves memory and spatial cognition in healthy adults. *Sci. Rep.* 7:5661. doi: 10.1038/s41598-017-06071-9

Schmidt, M., Egger, F., Kieliger, M., Rubeli, B., and Schüler, J. (2016). Gymnasts and orienteers display better mental rotation performance than nonathletes. *J. Individ. Differ.* 37, 1–7. doi: 10.1027/1614-0001/a000180

Sekiyama, K. (1982). Kinesthetic aspects of mental representations in the identification of left and right hands. *Percept. Psychophys.* 32, 89–95. doi: 10.3758/BF03204268

Shepard, R. N., and Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science* 171, 701–703. doi: 10.1126/science.171.3972.701

Shumway-Cook, A., and Woollacott, M.H. (2007). *Motor control: Translating research into clinical practice*. Philadelphia, PA Lippincott Williams & Wilkins.

Singh, H., and Wulf, G. (2022). Mind over body: creating an external focus for sport skills. *Eur. J. Sport Sci.* 22, 610–616. doi: 10.1080/17461391.2021.1887367

Steggemann, Y., Engbert, K., and Weigelt, M. (2011). Selective effects of motor expertise in mental body rotation tasks: comparing object-based and perspective transformations. *Brain Cogn.* 76, 97–105. doi: 10.1016/j.bandc.2011.02.013

Trivedi, P., and Rawal, H. (2020). A comparative study of physical and mental efficiency of badminton and volleyball players in Rajasthan. *Int. J. Phys. Educat. Sports Manag. Yogic Sci.* 10, 18–21.

Wulf, G., Lauterbach, B., and Toole, T. (1999). The learning advantages of an external focus of attention in golf. *Res. Q. Exerc. Sport* 70, 120–126. doi: 10.1080/02701367.1999.10608029

Wulf, G., Shea, C., and Lewthwaite, R. (2010). Motor skill learning and performance: a review of influential factors. *Med. Educ.* 44, 75–84. doi: 10.1111/j.1365-2923.2009.03421.x

Zartor, A. S., Mikheev, M. M., and Afanasiev, S. V. (2010). Lateral peculiarities of the process of mental rotation of the human body scheme. *J. Evol. Biochem. Physiol.* 46, 292–294. doi: 10.1134/S0022093010030117

frontiers | Frontiers in Psychology

TYPE Systematic Review
PUBLISHED 08 February 2024
DOI 10.3389/fpsyg.2024.1284787

Check for updates

OPEN ACCESS

EDITED BY
Kylie Ann Steel,
Western Sydney University, Australia

REVIEWED BY
David Sherwood,
University of Colorado Boulder, United States
Claire Thornton,
Northumbria University, United Kingdom

*CORRESPONDENCE
Youqiang Li
✉ youmecity@163.com

RECEIVED 29 August 2023
ACCEPTED 29 January 2024
PUBLISHED 08 February 2024

CITATION
Wu J, Qiu P, Lv S, Chen M and Li Y (2024) The effects of cognitive-motor dual-task training on athletes' cognition and motor performance.
Front. Psychol. 15:1284787.
doi: 10.3389/fpsyg.2024.1284787

The effects of cognitive-motor dual-task training on athletes' cognition and motor performance

Junyu Wu[1], Peng Qiu[2], Shuaibing Lv[1], Mingxian Chen[3] and Youqiang Li[1]*

[1]School of Physical Education, Shanghai University of Sport, Shanghai, China, [2]Department of Rehabilitation Medicine, The First Affiliated Hospital of Wenzhou Medical University, Wenzhou, Zhejiang, China, [3]School of Exercise and Health, Shanghai University of Sport, Shanghai, China

Background: Cognitive-Motor Dual Task (CMDT) training has been widely utilized in rehabilitation and sports practice. However, whether CMDT training can better enhance athletes' cognitive-motor performance compared to traditional single-task (ST) training remains unclear.

Method: A systematic review that complied with PRISMA was carried out (Prospero registration number: CRD42023443594). The electronic databases used for the systematic literature search from the beginning through 13 June 2023, included Web of Science, Embase, PubMed, and the Cochrane Library. After obtaining the initial literature, two researchers independently assessed it based on inclusion and exclusion criteria. Finally, the included literature was analyzed to compare the differences between ST training and CMDT training.

Results: After screening 2,094 articles, we included 10 acute studies and 7 chronic studies.

Conclusion: This systematic review shows that athletes typically show a degradation of performance in CMDT situations as opposed to ST when evaluated transversally. However, this performance decline is notably reduced following longitudinal training in CMDT, indicating the effectiveness of sustained CMDT training in enhancing cognitive-motor performance under dual-task conditions. Our study provides new insights into the application of CMDT in the field of sports training. Practitioners can utilize CMDT to assess athletic skill levels or optimize cognitive-motor performance of athletes, taking into account the specific needs of each sport.

Systematic review registration: https://www.crd.york.ac.uk/prospero, identifier CRD42023443594.

KEYWORDS

dual-task, cognitive-motor dual-task, athletes, cognitive performance, motor performance

1 Introduction

In the sphere of athletic development, it is argued that a training regimen which mirrors, to the highest degree possible, the demands inherent to actual competition yields the most substantial transfer effects on athletes' competitive performance (Murphy et al., 2016). Consequently, optimal training is posited to be that which converges with the reality of competition (Halouani et al., 2014; Murphy et al., 2016). The rapid advancement of modern competitive sports, along with the corresponding increase in competitive intensity among athletes, has given rise to this concept. Superior performances are often the emergent properties of a multifaceted matrix that intricately intertwines components such as rigorous training (Laursen and Jenkins, 2002; Smith, 2003; Sarmento et al., 2018), honed skills (Hrysomallis, 2011; Suchomel et al., 2016), and inherent talents (Smith, 2003; Breitbach et al., 2014; Varillas-Delgado et al., 2022). The progressive strides made in the fields of sports science and sports psychology have incrementally augmented our understanding of competition-centric training. Historically, the focus of inquiry gravitated predominantly toward the tangible, physical aspects of training, which included elements like fitness enhancement and technical skill refinement (Beattie et al., 2014; Wortman et al., 2021). However, the present-day narrative has witnessed a paradigmatic shift, with a surge in the number of researchers turning their investigative lens toward the pivotal role cognition plays within the sphere of athletic training (Broadbent et al., 2015; Slimani et al., 2016; Bühlmayer et al., 2017; Emirzeoğlu and Ülger, 2021). In the crucible of real-world competition, athletes are mandated to draw from a well-rounded skill set (Broadbent et al., 2015). This necessitates not only a sturdy foundation of physical robustness and technical prowess but also the ability to swiftly seize evanescent opportunities amidst complex athletic environments (Fuster et al., 2021). This dexterity enables athletes to execute a variety of technical maneuvers in a timely fashion, thereby optimizing their victory potential (Sabarit et al., 2020).

Consider the paradigm of a basketball match. A point guard, tasked with both dribbling and scanning the court, must maintain a keen awareness of the positions of teammates and opponents. This situational awareness allows the point guard to distribute the ball optimally, entrusting it to the player with the greatest opportunity at a given moment, hence setting the stage for an offensive maneuver. This scenario exemplifies the characteristic features of dual-tasking (DT; Bronstein et al., 2019), a subject of growing interest in contemporary sports research. Furthermore, extending this concept to incorporate the notion of "incorporated/added DT" as proposed by Herold et al. (2018) provides a more nuanced understanding of DT in sports contexts. This approach, differentiating from the traditional DT framework, involves the intentional addition of an extra cognitive task alongside the primary motor activity. For instance, a point guard engaged in regular dribbling and court scanning might also be tasked with an additional memory or attention challenge. This integrated approach enables a more precise evaluation of the interplay and coordination between cognitive and motor tasks, offering a means to control and quantify cognitive load in real-time sports situations. The application of "incorporated/added DT" methodology not only mirrors the complex realities of sports competitions but also allows for a deeper exploration into how athletes maintain a balance between motor skills and situational awareness under varying cognitive demands. Insights gained from this perspective are crucial for developing training methods that enhance cognitive-motor coordination and overall athletic performance, particularly in sports that demand high levels of strategic thinking and quick decision-making.

Traditional athletic training acknowledges the importance of periodized arrangement of individual training tasks, such as technique, physical fitness, tactics, and psychology, for optimizing athletes' performance to the maximum extent (Issurin, 2010; Hartmann et al., 2015). However, a fundamental difference exists between the actual demands faced by athletes who complete cognitive and motor tasks simultaneously in competitive scenarios and the training mode that involves sequentially completing technical and tactical exercises. This discrepancy may limit the transference effect of training. Therefore, researchers in sports science and psychology have gradually begun to pay attention to the cognitive-motor dual task (CMDT) training (Gabbett et al., 2011), which creatively combines specialized athletic techniques with cognitive tasks in the hopes of enhancing athletes' performance in actual competitions.

In the field of Cognitive-Motor Dual-Task (CMDT) training, distinct streams of research have emerged, each focusing on different applications and outcomes. Athletic training research primarily seeks theoretical and methodological advancement for performance enhancement. In this domain, studies have explored how CMDT can be utilized for the simultaneous development of physical and cognitive skills in professional athletes, such as in the training routines of NBA players like Jeremy Lin, who performs dribbling and arithmetic tasks concurrently. On the other hand, athletic rehabilitation research has been more focused on using CMDT for post-injury recovery. Much of the current evidence for the benefits of CMDT training, surprisingly, did not originate from athletic training research but rather from the fields of athletic rehabilitation and athletic practice (Pang et al., 2018; Gallou-Guyot et al., 2020; Tuena et al., 2023). CMDT has shown promise in improving patients' neuro-muscular functions and motor-cognitive abilities, aiding in the recovery of normal functions post-injury. This is evident in the improvement of physical functions and cognitive-motor performance in individuals with conditions like Parkinson's disease (Pereira-Pedro et al., 2022), stroke (Liu et al., 2017; Zhou et al., 2021), falls (Lord and Close, 2018). Furthermore, clinical research has demonstrated the significant contributions of CMDT in clinical risk assessment and prognostic evaluation. For instance, CMDT approaches combining walking and cognitive tasks are used to assess concussion risks in athletes or evaluate recovery statuses in concussion patients (Howell et al., 2017a,b).

Despite the accumulation of substantial evidence supporting CMDT training in areas such as rehabilitation therapy, current studies on CMDT within the sports science community is still in its infancy (Moreira et al., 2021). The exploration of CMDT training in the field of sports training remains limited, and the mechanisms and temporal progression of CMDT adaptation are still not fully understood (Moreira et al., 2021). For instance, while existing evidence has affirmed the potential benefits of CMDT on motor-cognitive performance, some studies have pointed out that the execution of DT in open-skilled sports is subject to strict time constraints (Baumeister, 1984). This may lead to an excessive cognitive load on individuals in a short time, causing a drastic decline in overall performance. Moreover, although previous systematic reviews have discussed the impact of DT training on athletes, the literature includes an excess of single cognitive type DT (Moreira et al., 2021), which clearly does not align with task characteristics during sports competition. Finally, due to considerable heterogeneity in CMDT intervention strategies for athletes in different sports, the applicability of this method in the field of sports remains indeterminable. Thus, the objective of this article is to systematically evaluate the impact of CMDT on the cognitive functions and athletic performance of athletes, in the hopes of providing a theoretical foundation for subsequent research, and offering guidance for coaches and related practitioners in formulating and adjusting sports training plans.

2 Methods

This systematic review is in alignment with the standards set by the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA; Moher et al., 2009; Prospero registration number: CRD42023443594), and the included literature is organized and analyzed in accordance with its requirements. Given the observed considerable heterogeneity in the methodologies and measurement methods of the included studies (please refer to the Supplementary Figures S1–S6), we are unable to conduct a meta-analysis.

2.1 Search strategy

This systematic review encompasses all literature available up to June 2023. Researchers Junyu Wu and Peng Qiu independently searched the PubMed, Web of Science (WOS), Embase, and Cochrane Library databases to find studies relevant to the topic. The search strategy was developed based on previous systematic reviews and was improved upon (Moreira et al., 2021). It is divided into the following parts: (1) dual task and its synonyms, (2) athletes and their synonyms, (3) athletic performance and its synonyms, (4) cognitive performance and its synonyms. Apart from the third and fourth components, which are joined by "OR," the rest of the parts are interconnected by "AND," constituting the search equation. The specific search string is as follows: "Cognitive motor" OR "dual task paradigm" OR "dual-task" OR "dual task" OR "double task" OR "multi-task" OR "divided attention" OR "secondary task" OR "second task" AND "athletes" OR "players" OR "player" OR "athlete" AND "working memory" OR "visual" OR "decision making" OR "gaze behavior" OR "attention" OR "athletic Performance" OR "athletic performances" OR "sports performance" OR "performance, sports."

2.2 Criteria for inclusion and exclusion

This systematic review adopts the PICO principles, as espoused by the Cochrane Collaboration, to establish the criteria for document inclusion. The established criteria are as follows: (1) Participants in the study comprise athletes at any competency level, emphasizing the universality of Cognitive-Motor Dual Tasking (CMDT). (2) The study concurrently reports on athletes' performance under both single-task (ST) and dual-task (DT) environments. (3) At a minimum, either cognitive performance or athletic performance of the athletes is reported. Exclusion criteria dictate the removal of a document under any of the following circumstances: (1) The presence of biomechanical studies investigating conditions under both ST and DT. (2) The participants are injured, cognitively impaired, or physically handicapped. (3) Dual-tasking does not involve a motor task or a cognitive task but merely constitutes the pairing of two tasks of the same type.

2.3 Data extraction

Data were extracted based on the established inclusion criteria, with the final data comprising the following elements: (1) Fundamental bibliographic details, including author names, title, and the year of publication; (2) Sample size; (3) Characteristics of the participants, including age, gender, training history, and level of skill; (4) Types of intervention strategies, encompassing acute or training interventions, duration of intervention periods, frequency, volume of training, specific intervention methods, etc.; and (5) Outcome measures, including primary outcome indicators and associated results. In cases of missing data within the literature, we reached out to the authors through email to request the missing data. We used Web Plot Digitizer software (Version 4.0; E, United States) to extract result data (mean ± standard deviation) reported only in graphic form. Two researchers independently extracted the data using tables, then merged the data. In cases of disagreement, a third researcher was consulted for a final decision.

Long-term studies are defined as those in which the intervention plan and period are clearly reported, with ST serving as the control group and CMDT as the experimental group. If there was no apparent CMDT plan and period, or if only a one-time report of ST and CMDT performances was provided, it was classified as an acute study. More accurately, acute studies only conduct transversal ST/CMDT evaluation, not training. In the incorporated acute studies, if certain participants failed to fulfill the inclusion and exclusion criteria, we confined our data extraction solely to the healthy athletes who satisfied these criteria. If in the included long-term studies multiple tests were conducted at different time points before and after the intervention, we only extracted baseline data before the intervention and immediate data after the intervention. If in the included long-term studies, multiple CMDT groups were compared with a control group (CON), we selected only the CMDT group with the lowest difficulty to minimize the impact of CMDT difficulty on intervention effects.

2.4 Risk of bias

To minimize potential biases in our result, we rigorously controlled the quality of the included literature and conducted quality assessments independently by two researchers (Junyu Wu and Peng Qiu). For the assessment, we adopted a modified version of the Quality Index Scale (Downs and Black, 1998), which reduced the number of evaluation questions from the original 24 to 14. This modified scale has been recently utilized and widely applied in similar studies within the field of sports (Bujalance-Moreno et al., 2019). The key dimensions assessed by the scale include: (1) clarity of the objectives, (2) clarity of the description of the primary outcomes to be measured, (3) clarity of the description of participant characteristics, (4) clarity of the description of the primary results, (5) presence of random variability estimation in the primary results, (6) clarity in the reporting of specific p-values associated with the primary results, (7) representativeness of the selected participants, (8) implementation of blinding, (9) clarity in describing data mining if utilized for primary data, (10) accuracy of the outcome measures for the primary results, (11) appropriateness of statistical tests employed for the primary results, (12) allocation of subjects (experimental design, case–control, or cohort study), (13) random assignment of subjects to intervention groups, and (14) adjustment for confounding factors in the analysis of the main conclusions. Each question is typically answered in a "Yes/No" format, where each "Yes" response earns one point and a “No” response scores zero, thereby enabling the scoring of the overall quality of the study. The findings from the assessment of risk bias are detailed in Tables 1, 2.

3 Results

Figure 1 illustrates the flowchart detailing the literature retrieval process. As Figure 1 indicates, our search through the aforementioned four databases yielded 2,094 articles. Duplicate entries were eliminated using Endnote 9.1X, leaving a total of 1,833 articles. An initial screening, predicated on the examination of titles and abstracts, pinpointed documents that satisfied the inclusion and exclusion criteria, leading to the selection of 96 articles that necessitated a detailed review. Ultimately, 28 studies were incorporated into the review, with 21 studies examining the acute effects of ST and DT, and 7 studies evaluating long-term effects. Two independent researchers (Junyu Wu and Peng Qiu), conducted each step of the process. In instances of disagreement, a third researcher (Youqiang Li), jointly adjudicated on the inclusion of the document.

Tables 1, 2 present the quality assessment results of the acute and chronic studies, respectively. According to Table 1, the highest quality score among the acute studies was 1, and the lowest was 0.75. According to Table 2, the highest quality score among the chronic studies was 0.92, and the lowest was 0.83. These result indicates that the articles included in our study demonstrate a moderate to high level of quality.

Table 3 shows the cognitive-motor performance of subjects during the transversal ST and CMDT evaluation in each acute study (total 10 articles). The primary objectives of these studies can be categorized as follows: (1) To simulate a match or a critical part of a match (with a much higher cognitive load) using the CMDT in order to assess athletes’ mastery of motor skills in this complex scenario. (2) Investigating the performance differences between high-level and low-level athletes in ST and CMDT situations, thereby demonstrating the superior sensitivity of CMDT acute assessments over ST. These two types of studies usually involve creating a situation highly similar to a particular sport, where athletes complete a primary sport-related task (such as tennis, volleyball, football, table tennis, soccer, fencing, etc.) while simultaneously undertaking a cognitive task (primarily auditory, visual, memory, or arithmetic tasks). Except for one sub-group in one study that reported superior DT performance under CMDT conditions compared to ST (the study of Amico and Schaefer, 2022 where high-level tennis players achieved a higher number of hits under DT conditions compared to ST), all acute studies reported superior performance under ST than DT, regardless of whether it is cognitive or motor performance.

Table 4 presents the basic information of the long-term studies included in this review. This systematic review incorporated seven long-term studies related to the impact of ST and CMDT on the cognitive-motor performance of athletes. The purpose of all long-term studies was to improve the adaptability of athletes to CMDT, with the aim of enhancing the transfer effect of general cognitive ability or specific athletic ability, thereby improving the cognitive-motor performance of athletes. Generally speaking, all included studies reported a significant improvement in most indicators of cognitive-motor performance in athletes after CMDT training intervention, with only a few indicators showing no statistical difference in improvement compared to ST training.

The seven studies were individually focused on various sports (football, rugby, basketball, badminton, beach volleyball), and as a result, the athletic tasks were formulated to reflect the particular skills demanded by each of these sports. In six out of the seven studies, cognitive tasks involved visual response tasks or 3D multi-target tracking tasks, and only one study implemented the

TABLE 1 Literature quality assessment of acute effects studies.

Item code	1	2	3	6	7	10	12	15	16	18	20	22	23	25	Final score
Amico and Schaefer (2022)	1	1	1	1	1	1	1	U	1	1	1	1	U	1	1
Fleddermann and Zentgraf (2018)	1	1	1	1	1	1	0	U	1	1	1	1	U	1	0.92
Gabbett et al. (2011)	1	1	0	1	1	1	0	U	1	1	1	1	U	1	0.83
Gabbett and Abernethy (2012)	1	1	1	1	1	1	1	U	1	1	1	1	U	1	1
Gabbett and Abernethy (2013)	1	1	0	1	1	1	1	U	1	1	1	1	U	1	0.92
Sarto et al. (2020)	1	1	1	1	1	1	1	U	1	1	1	1	U	1	1
Schaefer and Scornaienchi (2020)	1	1	1	1	0	1	1	U	1	1	1	1	U	1	0.92
Gutiérrez-Davila et al. (2017)	1	1	1	1	1	0	0	U	1	1	0	1	U	1	0.75
Van Biesen et al. (2018)	1	1	1	1	1	1	0	U	1	1	1	1	U	1	0.92
Laurin and Finez (2020)	1	1	1	1	0	1	1	U	1	0	0	1	U	1	0.75

U, unclear. Item 1, Is the hypothesis/aim/objective of the study clearly described?; Item 2, Are the main outcomes to be measured clearly described in the Introduction or Methods sections?; Item 3, Are the characteristics of the patients included in the study clearly described?; Item 6, Are the main findings of the study clearly described?; Item 7, Does the study provide estimates of the random variability in the data for the main outcomes?; Item 10, Have actual probability values been reported (e.g., 0.035 rather than < 0.05) for the main outcomes, except where the probability value is less than 0.001?; Item 12, Were those subjects who were prepared to participate representative of the entire population from which they were recruited?; Item 15, Was an attempt made to blind those measuring the main outcomes of the intervention?; Item 16, If any of the results of the study were based on “data dredging,” was this made clear?; Item 18, Were the statistical tests used to assess the main outcomes appropriate?; Item 20, Were the main outcome measures used accurate (valid and reliable)?; Item 22, Were study subjects in different intervention groups (trials and cohort studies), or were the cases and controls (case–control studies) recruited over the same period?; Item 23, Were study subjects randomized to intervention groups?; Item 25, Was there an adequate adjustment for confounding in the analyses from which the main findings were drawn?

TABLE 2 Literature quality assessment of chronic effects studies.

Item code	1	2	3	6	7	10	12	15	16	18	20	22	23	25	Final score
Casella et al. (2022)	1	1	0	1	1	1	1	U	1	1	1	1	U	1	0.92
Gabbett et al. (2011)	1	1	0	1	1	0	1	U	1	1	1	1	U	1	0.83
Lucia et al. (2021)	1	1	0	1	1	1	1	U	1	1	1	1	U	1	0.92
Lucia et al. (2023)	1	1	0	1	1	1	1	U	1	1	1	1	U	1	0.92
Lucia et al. (2023)	1	1	0	1	1	1	1	U	1	1	1	1	U	1	0.92
Romeas et al. (2019)	1	1	0	1	1	1	1	U	1	1	1	1	U	1	0.92
Fleddermann et al. (2019)	1	1	1	1	0	1	1	U	1	1	1	1	U	1	0.92

U, unclear; Item 1, Is the hypothesis/aim/objective of the study clearly described?; Item 2, Are the main outcomes to be measured clearly described in the Introduction or Methods sections?; Item 3, Are the characteristics of the patients included in the study clearly described?; Item 6, Are the main findings of the study clearly described?; Item 7, Does the study provide estimates of the random variability in the data for the main outcomes?; Item 10, Have actual probability values been reported (e.g., 0.035 rather than <0.05) for the main outcomes, except where the probability value is less than 0.001?; Item 12, Were those subjects who were prepared to participate representative of the entire population from which they were recruited?; Item 15, Was an attempt made to blind those measuring the main outcomes of the intervention?; Item 16, If any of the results of the study were based on "data dredging," was this made clear?; Item 18, Were the statistical tests used to assess the main outcomes appropriate?; Item 20, Were the main outcome measures used accurate (valid and reliable)?; Item 22, Were study subjects in different intervention groups (trials and cohort studies), or were the cases and controls (case–control studies) recruited over the same period?; Item 23, Were study subjects randomized to intervention groups?; Item 25, Was there an adequate adjustment for confounding in the analyses from which the main findings were drawn?

task through auditory stimulation. Given the different demands for CMDT by different sports, coupled with significant variances in specific athletic tasks, considerable heterogeneity exists in the design of intervention methods in different studies. The methods for measuring outcome indicators also varied. In the arrangement of training plans, differences are present in key variables such as intervention duration, frequency, among different studies (including one study that did not report the duration of single interventions and weekly training frequency). Within the six long-term studies detailing the duration of individual interventions, the length of single training sessions fluctuated between 22 and 90 min. The predominant training frequency was set at twice a week, and the intervention periods extended from 5 to 10 weeks.

4 Discussion

This systematic review amalgamates and analyzes relevant literature, revealing that that athletes typically experience a degradation in performance under CMDT compared to ST when assessed transversally. However, the implementation of long-term CMDT has been observed to augment cognitive-motor performance in athletes. Within the body of literature investigated in this review, acute CMDT studies are primarily employed to evaluate athletes' tactical skill levels. Conversely, long-term CMDT is treated as a supplementary training modality designed to induce positive adaptation in athletes through sustained stimuli, thereby bolstering cognitive-motor performance in specified contexts. These findings substantiate the long-term advantages of CMDT in the domain of athletic training. Based on the existing body of evidence, CMDT emerges as a potent adjunct training tool within the sphere of sports training, poised to enhance the cognitive-motor performance in athletes engaged in cognitively demanding sports. Additionally, these insights lay the groundwork for sports training professionals, including coaches and athletes, to acquire a more nuanced comprehension of the time-related dynamics and evolutionary trends in CMDT training. This knowledge will empower them to craft or refine training regimens to optimize athletes' performance.

Our findings are consistent with those of previous studies, which concluded that transversal CMDT evaluation typically lead to a sharp decline in athletes' performance compared to ST (Moreira et al., 2021). However, as the athlete gradually acclimatizes to this unique stimulus, sustained exposure to CMDT ultimately leads to an improvement in their cognitive-motor performance. This abrupt reduction in performance in response to an acute CMDT can be accounted for by the cognitive load theory (Baumeister, 1984; Fuster et al., 2021). According to this theory, an individual's working memory capacity is finite. In this context, type 2 processing refers to slow, deliberate, and effortful cognitive activities, which are more resource-intensive and can only manage a limited amount of information within a specified period (Furley et al., 2015). In a CMDT scenario, when an ancillary task abruptly elevates the cognitive load, a "choking" effect ensues, ultimately resulting in a sharp decline in performance (Baumeister, 1984; Moher et al., 2009). This performance drop appears to be closely tied to the level of the athlete's training and the complexity of the CMDT. For example, studies have shown that athletes of higher competence deliver superior performance under CMDT conditions (Gabbett and Abernethy, 2012; Schaefer and Scornaienchi, 2020; Amico and Schaefer, 2022). Interestingly, in Amico et al.'s study, elite tennis players even hit the ball more in the DT than in the ST situation (Amico and Schaefer, 2022). According to DT effect model as described by Plummer et al. (2014), the exceptional performance observed in Amico 2022's study under CMDT conditions may be indicative of the elite athletes' ability to optimize task management and resource allocation, resulting in enhanced performance. Notably, Gabbett et al. (2011) even used a specialized CMDT test in rugby as a tool to assess the technical level of national-grade rugby athletes. While earlier studies suggested that athletes with a wealth of professional experience, attributed to their superior working memory capacity, can excel under CMDT conditions, recent studies indicate that a superior working memory capacity does not invariably lead to improved DT performance (Laurin and Finez, 2020). Although a majority of studies confirm the importance of working memory capacity in enhancing DT performance (Baumeister, 1984; Furley et al., 2015; Moreira et al., 2021), additional studies are necessary to unravel this intricate mechanism. Further, there

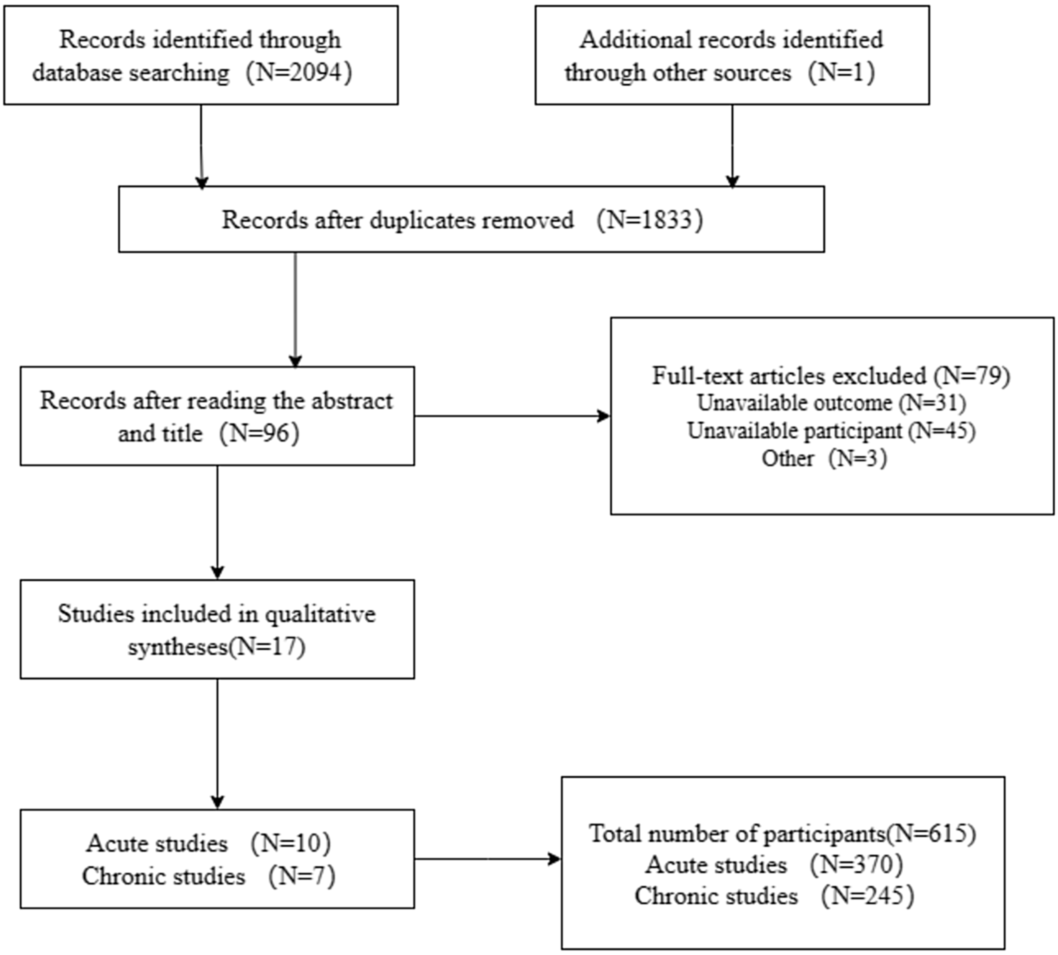


FIGURE 1
Flow chart of literature search steps.

is a discernible correlation between the complexity of CMDT and performance (Gabbett et al., 2011; Gabbett and Abernethy, 2012). In an assessment of this correlation, (Gabbett et al., 2011) compared the CMDT performance of national-level rugby players under 2 vs. 1, 3 vs. 2, and 4 vs. 3 passing scenarios, revealing a decline in performance as the offense-defense scenarios grew increasingly complex. Importantly, their series of studies have found that, under real match conditions, the frequency of utilizing these techniques in 2 vs. 1, 3 vs. 2, and 4 vs. 3 scenarios progressively decreases. Due to a high turnovers rate, athletes barely employ this technique in 4 vs. 3 situations.

In actual sports competitions, the influence of acute Cognitive-Motor Dual-Task (CMDT) on the cognitive-motor performance of athletes is more intricate than initially apparent. It is not only subject to interference from the surge in cognitive load under DT conditions, but the physiological load on the athletes also impacts their performance (Schapschröer et al., 2016). As athletes grow increasingly fatigued, their cognitive function correspondingly declines, leading to a rise in decision-response time and error rate (Schapschröer et al., 2016). Conversely, when the cognitive load on an athlete surges, type 2 processing allocates more working memory to the cognitive task. The scattered attention subsequently results in a significant drop in the execution efficiency of the motor task, culminating in an overall performance decline (Baumeister, 1984). Given that the cognitive-motor performance of athletes on the field is influenced by the interplay of physiological load and cognitive load, we posit that it is necessary to introduce CMDT as a supplementary training regimen in sports that demand high cognitive loads, such as team ball games. This strategy will help athletes better manage the intricacies of performing simultaneous cognitive and motor tasks during competition, potentially leading to improved performance. Furthermore, an athlete's capability to swiftly and accurately interpret the dynamic elements of the game (Piras et al., 2014; Roca et al., 2018; Li et al., 2023), such as displacement direction and velocity of teammates, opponents, and objects like the ball, is pivotal. Rapidly adapting to these ever-changing spatial and temporal factors is a critical aspect of cognitive-motor coordination (Li et al., 2023). In team ball sports, for example, players must not only be cognizant of the present positions of others but also adept at predicting and responding to their potential trajectories and speeds. This heightened spatial–temporal awareness is essential for making strategic decisions and executing precise physical actions (Voyer and Jansen, 2017). Consequently, incorporating training elements in CMDT that emphasize skill development in perceiving and responding to these dynamic displacements is vital for optimizing cognitive and motor task performance.

TABLE 3 Effects of acute CMDT on athletes' cognitive-motor performance.

References	Participant	Age	Level	Task	Major outcome	Result	Value of *p*
Amico and Schaefer (2022)	24 tennis athletes medium expertise (12) high expertise (12)	20.2 ± 2.9 21.9 ± 3.6	German Tennis Federation 1–23	ST: tennis returns.	3-back score, number of hits	3-back score ST > DT	<0.05
				DT:3-back task+ tennis returns.		Number of hits ST > DT (medium) ST < DT (High)	<0.05
Fleddermann and Zentgraf (2018)	24 beach volleyball players (21 women and 3 men)	19.2 ± 4.2	National	ST: volleyball block	Decision-making, jump height, and stride length	Jump height = ST > DT	<0.05
				DT: volleyball block +visual stimulus		Stride length = ST > DT	<0.05
						Decision-making (error) = ST < DT	Not reported
Gabbett et al. (2011)	37 ruby players	17.3 ± 0.9	National state	ST:2-on-1 situation	Draw and pass proficiency, verbal reaction times, tone recognition accuracy	Draw and pass proficiency: ST > DT (low) ST > DT (high)	low:<0.05
	20 high-level	17.1 ± 0.2		DT:2-on-1 situation + verbal tone recognition task			high: >0.05
						verbal reaction times: ST < DT	<0.05
	17 lesser-level					Tone recognition accuracy: ST > DT	<0.05
Gabbett and Abernethy (2012)	12 high-level ruby players	22.9 ± 0.9	National	ST:2-on-1 situation/3-on-2 situation	Cognitive errors, draw and pass proficiency, verbal reaction time, response accuracy	Verbal reaction time: ST < DT	<0.05
				DT:2-on-1 situation/3-on-2situation + arithmetic manipulation		Response accuracy: ST < DT	<0.05
						Draw and pass proficiency (2 on 1):ST < DT	>0.05
						Draw and pass proficiency (3 on 2):ST > DT	>0.05
Gabbett and Abernethy et al. (2013)	88 rugby league players		National	ST: anticipation test	Verbal reaction time, response accuracy	Whether primary or secondary mission	>0.05
						Verbal reaction time: ST < DT	
				DT: anticipation test+ verbal tone recognition		Response accuracy: ST < DT	>0.05
Sarto et al. (2020)	19 endurance athletes	28.32 ± 4.59	Not reported	ST: DPB/SPB	DPB performance, SPB performance, cognitive performance	DBP performance: ST > DT	END:<0.05
						SBP performance: ST > DT	TA:>0.05
	16 team athletes	23.44 ± 2.49		DT: SPB + Subtractive tasks		Cognitive performance	<0.05
Schaefer and Scornaienchi (2020)	22 table tennis players (7 women and 15 men,11 experts and 11 novices)	25.5 ± 2.6	Not reported	ST: technical and tactical task	Accuracy; working memory capacity	Technical-tactical accuracy: experts = ST > DT, novices = ST > DT; working memory capacity: experts = ST > DT, novices = ST > DT	<0.05
		23.6 ± 2.2		DT: technical and tactical task + working memory task (3-back test)			<0.05
							<0.05
Van Biesen et al. (2018)	103 athletes (33females and 70 males)	22.0 ± 2.4	Amateur	ST: multiple object tracking task	Multiple object tracking task accuracy, static balance control performance	Multiple object tracking task accuracy: ST > DT	<0.05
				DT: multiple object tracking task+ balance task		Performance in the balance task: ST > DT	<0.05

(Continued)

TABLE 3 (Continued)

References	Participant	Age	Level	Task	Major outcome	Result	Value of *p*
Gutiérrez-Davila et al. (2017)	25 fencing players (15 men and 10 women)	Homens:21.1 ± 4.9	Elite	ST: attacking actions against an opponent after a pre-established visual stimulus	Reaction time; speed in the attacking actions; technical-tactical offensive and defensive performance	Reaction time: DT > ST	>0.05
		Mulheres:21.4 ± 2.3		DT: an attentional task in which players were required to react differently to visual stimuli in the trunk and the head.		Speed of attack actions: ST > DT	<0.05
						Technical-tactical defensive performance: ST > DT	<0.05
Laurin and Finez (2020)	90 male soccer players	Study 1:19.2 ± 1.3	College	ST: juggling performance	Performance in juggling performance	Technical performance = ST > DT	<0.05
		Study 2:19.2 ± 1.1		DT: juggling performance + perform arithmetic subtraction operations + count down from 3 by 3 from 300 juggling performance + multiplication task			
		Study 3:19.9 ± 1.3					

ST, single-task; DT, cognitive-motor dual-task; DPB, Dynamic postural balance; SPB, Static postural balance. For acute studies, a common approach is conducting mixed-design analysis of variance (ANOVA). In this Table, we have provided a concise summary of the statistical values pertaining to the main effects of task types. For a more comprehensive set of statistical details, we recommend referring to the original text.

While previous studies have supported the potential benefits of long-term DT training for athletes, the systematic review of Moreira et al. (2021) did not specifically discuss the application of CMDT in the field of sports training. Considering the cognitive-motor demands and the interaction between physiological and cognitive loads in athletes' real-life competitive scenarios, we excluded all DT studies that focused on a single cognitive or motor task. The results remained consistent. However, among all the included long-term studies, only few studies quantified athletes' cognitive load and physiological load, and none of the studies objectively quantified physiological load using specific metrics. This lack of quantification of physiological load poses challenges in explaining the long-term effects of CMDT. Subsequent research should include pertinent measures to gauge load, enhancing the understanding of the sustained effects of CMDT.

Currently, the underlying mechanisms through which CMDT enhances cognitive-motor performance in athletes remain unclear. Prior research indicates that DT training enhances the evolution of perceptual-cognitive strategies by augmenting attentional distribution and aiding in the discernment of crucial details relevant to the task (Bherer et al., 2008). For instance, Ducrocq et al. (2017) found that DT training significantly increased the duration of fixations, thereby providing more informative cues for tactical analysis and decision-making. Additionally, the Allocation and Scheduling Hypothesis (Strobach, 2020), as a classical theory explaining the long-term training effects of CMDT, offers another perspective on athletes' performance improvements following CMDT training. This hypothesis posits that CMDT training enhances the allocation and scheduling of cognitive resources in integrated tasks, thereby enhancing CMDT performance. For example, Fleddermann and Zentgraf (2018) observed improvements in sustained attention and processing speed, contributing to enhanced CMDT performance. Furthermore, recent studies by Lucia et al. (2021, 2023), utilizing event-related potentials in a series of investigations involving semi-professional adolescent basketball players, suggest that the potential mechanisms underlying the long-term effects of CMDT may involve enhanced anticipatory brain processing capabilities in the prefrontal cortex along with increased post-perceptual activity associated with decision-making. They propose that CMDT can modulate cognitive functioning through neuroplasticity processes in the brain to achieve specific sport-related goals (Lucia et al., 2021).

Although this systematic review provides new insights into the application of CMDT in sports training, it has several limitations. Firstly, the systematic review included studies that generally lacked detailed descriptions of key training variables. For instance, intensity, inter-set rest periods, cognitive load, and physiological load were often inadequately reported. Even when some studies described athletes' physiological and cognitive loads, the measurement methods were often subjective, lacking objective indicators. This makes it difficult to discern the relationship between load and adaptation while also reducing the practical applicability of research findings in real-world settings. Secondly, the majority of studies, especially those investigating acute effects, tended to be conducted in laboratory settings, which presents a challenge in simulating game elements as closely as possible. To promote the widespread adoption of CMDT training methods in sports, future studies should aim to conduct studies in sports-specific environments. Previous studies have suggested that conducting small-sided games or game simulations on sports fields helps replicate real tactical and technical situations (Davids et al., 2013), which would be more meaningful in the context of sports training. Lastly, the notable variation in participant characteristics,

TABLE 4 Effects of chronic CMDT on athletes' cognitive-motor performance.

References	Participant	Age	Level	Task	Major outcome	Result	p-values
Casella et al. (2022)	24 children soccer athletes	10 ± 0.4	Not reported	ST: soccer training	TOL test	TOL (error):CON>EXP	<0.05
				DT: soccer training +voice task	WISC-IV cancelation test	WISC-IV: CON<EXP	<0.05
				regimen: 10 weeks, 2 times/ week, 22 min/time as a supplement to regular training		TOL (score):CON<EXP	<0.05
Gabbett et al. (2011)	21 high-level ruby players	17.3 ± 0.9	National	ST:2-on-1 situation/3-on-2 situation	Cognitive errors, draw and pass proficiency, verbal reaction time, response accuracy	Draw and pass proficiency (ST condition)	<0.05
				DT:2-on-1 situation/3-on-2 situation +arithmetic manipulation			
				training regimen:8 weeks, sessions 3–5 involved 2-on-1 drills the final three training sessions involved simple 3-on-2 drills		ST<DT draw and pass proficiency (DT condition) ST < DT	<0.05
Lucia et al. (2021)	52 basketball athletes (females 28 males 24)	16.33 ± 1.1	Semi-elite	ST: dribbling tasks	Response times, false alarms, single change tests completion time, Multiple change tests completion time	Single change tests completion time: ST > DT	<0.05
				DT: dribbling tasks+ visual task training		Multiple change tests completion time: ST > DT	<0.05
				Regimen:5 weeks, 2 times a week, 30 min/time as individual technical training		Response times: ST > DT	<0.05
						False alarms: ST > DT	<0.05
Lucia et al. (2023)	24 young male semi-elite	16.6 ± 1.1	Semi-elite	ST: dribbling tasks	5 kinds of basketball dribbling, commission error	5 kinds of basketball dribbling performance: DT > ST	<0.05
				DT: dribbling tasks+ visual task			
	Basketball players			Training regimen:5 weeks,2 times/ week,30 min/time as individual technical training		Commission error: ST > DT	<0.05
Lucia et al. (2023)	52 young semi-elite basketball players (28 females and 24 males)	16.1 ± 1.1 16.5 ± 1.2	Semi-elite	ST: dribbling tasks	single change tasks completion time, multiple change tasks completion time. Response time, commission errors.	single change tests completion time: ST > DT	<0.05
						Multiple change tests completion time: ST > DT	<0.05
				DT: dribbling tasks+ visual task		Response times: ST > DT	<0.05
				Training regimen:5 weeks,2 times/ week, 30 min/time as individual technical training		Commission errors: ST > DT	<0.05
Romeas et al. (2019)	29 badminton players (6 women and 23 men).	22.98 ± 2.77	Amateur	ST:3D-MOT training	Visual behavior, working memory capacity, decision-making tasks accuracy, reaction times,	Reaction times: ST > DT	<0.05
				DT:3D-MOT training + badminton birdie interceptions		Decision-making tasks accuracy: ST < DT	<0.05
				Training regimen:12 times (30 min/time 9times, 90 min/ time 3times)		Working memory Capability: ST < DT	<0.05
						Visual behavior: no significant	>0.05

(Continued)

TABLE 4 (Continued)

References	Participant	Age	Level	Task	Major outcome	Result	p-values
Fleddermann et al. (2019)	43 beach volleyball players, intervention group 22 (2 men and 20 women) and control group 21 (5 men and 16 women)	Intervention group:16.38 ± 1.7	Elite	DT: the specific or nonspecific motor task of volleyball +3D-motion task. training regimen: 8 weeks with 2time/week, 30 min/time. Each block comprised 3 sessions, 8 min each with a 3 min break in-between.	Working memory capacity; jump height in a specific task (beach volleyball); accuracy in 3D motion task; attentional capacity; processing speed	Performance in the 3D motion task: DT > ST	<0.05
						Sustained attention: DT > ST	<0.05
						Processing speed: DT > ST	<0.05
		Control group:21.38 ± 4.53				Jump height: ST > DT	<0.05
						Working memory capacity: no significant difference between groups and time.	>0.05

ST, single-task; DT, cognitive-motor dual-task; 3D-MOT, three-dimensional multiple object tracking; TOL, Tower of London; 5 kinds of basketball dribbling including crossover, double crossover, between legs, crossover + between legs, between legs + behind.

such as age, gender, and sports proficiency, combined with diverse methodological approaches in the field, has presented challenges in synthesizing research findings. To address this issue, future studies should focus on minimizing these differences by adopting more uniform and standardized methods in Cognitive-Motor Dual-Task (CMDT) training research.

In summary, future CMDT experimental research aiming to enhance athletes' cognitive-motor performance should be conducted as much as possible in real sports settings, with an emphasis on detailed reporting of key training variables to better facilitate optimal cognitive-motor performance in athletes.

5 Conclusion

This systematic review posits that athletes generally exhibit a decline in cognitive-motor performance when assessed transversally CMDT, as compared to ST. However, in contrast to ST training, athletes demonstrate a more pronounced improvement in cognitive-motor performance following prolonged CMDT training. Our study provides new insights into the application of CMDT in the field of sports training. Practitioners can utilize CMDT to assess athletic skill levels or optimize cognitive-motor performance of athletes, taking into account the specific needs of each sport.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JW: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Supervision. PQ: Data curation, Formal analysis, Methodology, Writing – original draft. SL: Conceptualization, Data curation, Formal analysis, Writing – review & editing. MC: Data curation, Methodology, Writing – review & editing. YL: Supervision, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

The authors thank PQ colleagues for their help with the study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2024.1284787/full#supplementary-material

References

Amico, G., and Schaefer, S. (2022). Tennis expertise reduces costs in cognition but not in motor skills in a cognitive-motor dual-task condition. *Acta Psychol.* 223:103503. doi: 10.1016/j.actpsy.2022.103503

Baumeister, R. F. (1984). Choking under pressure: self-consciousness and paradoxical effects of incentives on skillful performance. *J. Pers. Soc. Psychol.* 46, 610–620. doi: 10.1037//0022-3514.46.3.610

Beattie, K., Kenny, I. C., Lyons, M., and Carson, B. P. (2014). The effect of strength training on performance in endurance athletes. *Sports Med.* 44, 845–865. doi: 10.1007/s40279-014-0157-y

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., and Becic, E. (2008). Transfer effects in task-set cost and dual-task cost after dual-task training in older and younger adults: further evidence for cognitive plasticity in attentional control in late adulthood. *Exp. Aging Res.* 34, 188–219. doi: 10.1080/03610730802070068

Breitbach, S., Tug, S., and Simon, P. (2014). Conventional and genetic talent identification in sports: will recent developments trace talent? *Sports Med.* 44, 1489–1503. doi: 10.1007/s40279-014-0221-7

Broadbent, D. P., Causer, J., Williams, A. M., and Ford, P. R. (2015). Perceptual-cognitive skill training and its transfer to expert performance in the field: future research directions. *Eur. J. Sport Sci.* 15, 322–331. doi: 10.1080/17461391.2014.957727

Bronstein, M. V., Pennycook, G., Joormann, J., Corlett, P. R., and Cannon, T. D. (2019). Dual-process theory, conflict processing, and delusional belief. *Clin. Psychol. Rev.* 72:101748. doi: 10.1016/j.cpr.2019.101748

Bühlmayer, L., Birrer, D., Röthlin, P., Faude, O., and Donath, L. (2017). Effects of mindfulness practice on performance-relevant parameters and performance outcomes in sports: a Meta-analytical review. *Sports Med.* 47, 2309–2321. doi: 10.1007/s40279-017-0752-9

Bujalance-Moreno, P., Latorre-Román, P., and García-Pinillos, F. (2019). A systematic review on small-sided games in football players: acute and chronic adaptations. *J. Sports Sci.* 37, 921–949. doi: 10.1080/02640414.2018.1535821

Casella, A., Ventura, E., and Di Russo, F. (2022). The influence of a specific cognitive-motor training protocol on planning abilities and visual search in young soccer players. *Brain Sci.* 12. doi: 10.3390/brainsci12121624

Davids, K., Araújo, D., Correia, V., and Vilar, L. (2013). How small-sided and conditioned games enhance acquisition of movement and decision-making skills. *Exerc. Sport Sci. Rev.* 41, 154–161. doi: 10.1097/JES.0b013e318292f3ec

Downs, S. H., and Black, N. (1998). The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *J. Epidemiol. Community Health* 52, 377–384. doi: 10.1136/jech.52.6.377

Ducrocq, E., Wilson, M., Smith, T. J., and Derakshan, N. (2017). Adaptive working memory training reduces the negative impact of anxiety on competitive motor performance. *J. Sport Exerc. Psychol.* 39, 412–422. doi: 10.1123/jsep.2017-0217

Emirzeoğlu, M., and Ülger, Ö. (2021). The acute effects of cognitive-based neuromuscular training and game-based training on the dynamic balance and speed performance of healthy young soccer players: a randomized controlled trial. *Games Health J* 10, 121–129. doi: 10.1089/g4h.2020.0051

Fleddermann, M. T., Heppe, H., and Zentgraf, K. (2019). Off-court generic perceptual-cognitive training in elite volleyball athletes: task-specific effects and levels of transfer. *Front Psychol.* 10:1599. doi: 10.3389/fpsyg.2019.01599

Fleddermann, M. T., and Zentgraf, K. (2018). Tapping the full potential? Jumping performance of volleyball athletes in game-like situations. *Front. Psychol.* 9:1375. doi: 10.3389/fpsyg.2018.01375

Furley, P., Schweizer, G., and Bertrams, A. (2015). The two modes of an athlete: dual-process theories in the field of sport. *Int. Rev. Sport Exerc. Psychol.* 8, 106–124. doi: 10.1080/1750984x.2015.1022203

Fuster, J., Caparrós, T., and Capdevila, L. (2021). Evaluation of cognitive load in team sports: literature review. *PeerJ* 9:e12045. doi: 10.7717/peerj.12045

Gabbett, T. J., and Abernethy, B. (2012). Dual-task assessment of a sporting skill: influence of task complexity and relationship with competitive performances. *J. Sports Sci.* 30, 1735–1745. doi: 10.1080/02640414.2012.713979

Gabbett, T. J., and Abernethy, B. (2013). Expert–novice differences in the anticipatory skill of rugby league players. *Sport* 2, 138–155.

Gabbett, T., Wake, M., and Abernethy, B. (2011). Use of dual-task methodology for skill assessment and development: examples from rugby league. *J. Sports Sci.* 29, 7–18. doi: 10.1080/02640414.2010.514280

Gallou-Guyot, M., Mandigout, S., Bherer, L., and Perrochon, A. (2020). Effects of exergames and cognitive-motor dual-task training on cognitive, physical and dual-task functions in cognitively healthy older adults: an overview. *Ageing Res. Rev.* 63:101135. doi: 10.1016/j.arr.2020.101135

Gutiérrez-Davila, M., Rojas, F. J., Gutiérrez-Cruz, C., and Navarro, E. (2017). Effect of dual-attention task on attack and defensive actions in fencing. *Eur. J. Sport Sci.* 17, 1004–1012. doi: 10.1080/17461391.2017.1332100

Halouani, J., Chtourou, H., Gabbett, T., Chaouachi, A., and Chamari, K. (2014). Small-sided games in team sports training: a brief review. *J. Strength Cond. Res.* 28, 3594–3618. doi: 10.1519/jsc.0000000000000564

Hartmann, H., Wirth, K., Keiner, M., Mickel, C., Sander, A., and Szilvas, E. (2015). Short-term periodization models: effects on strength and speed-strength performance. *Sports Med.* 45, 1373–1386. doi: 10.1007/s40279-015-0355-2

Herold, F., Hamacher, D., Schega, L., and Müller, N. G. (2018). Thinking while moving or moving while thinking—concepts of motor-cognitive training for cognitive performance enhancement. *Front. Aging Neurosci.* 10:228. doi: 10.3389/fnagi.2018.00228

Howell, D. R., Beasley, M., Vopat, L., and Meehan, W. P. (2017a). The effect of prior concussion history on dual-task gait following a concussion. *J. Neurotrauma* 34, 838–844. doi: 10.1089/neu.2016.4609

Howell, D. R., Oldham, J. R., DiFabio, M., Vallabhajosula, S., Hall, E. E., Ketcham, C. J., et al. (2017b). Single-task and dual-task gait among collegiate athletes of different sport classifications: implications for concussion management. *J. Appl. Biomech.* 33, 24–31. doi: 10.1123/jab.2015-0323

Hrysomallis, C. (2011). Balance ability and athletic performance. *Sports Med.* 41, 221–232. doi: 10.2165/11538560-000000000-00000

Issurin, V. B. (2010). New horizons for the methodology and physiology of training periodization. *Sports Med.* 40, 189–206. doi: 10.2165/11319770-000000000-00000

Laurin, R., and Finez, L. (2020). Working memory capacity does not always promote dual-task motor performance: the case of juggling in soccer. *Scand. J. Psychol.* 61, 168–176. doi: 10.1111/sjop.12589

Laursen, P. B., and Jenkins, D. G. (2002). The scientific basis for high-intensity interval training: optimising training programmes and maximising performance in highly trained endurance athletes. *Sports Med.* 32, 53–73. doi: 10.2165/00007256-200232010-00003

Liu, Y. C., Yang, Y. R., Tsai, Y. A., and Wang, R. Y. (2017). Cognitive and motor dual task gait training improve dual task gait performance after stroke—a randomized controlled pilot trial. *Sci. Rep.* 7:4070. doi: 10.1038/s41598-017-04165-y

Li, Y., Feng, T., Zhang, F., Asgher, U., Yan, B., and Peng, T. (2023). Visual search strategies of performance monitoring used in action anticipation of basketball players. *Brain Behav.* 13:e3298. doi: 10.1002/brb3.3298

Lord, S. R., and Close, J. C. T. (2018). New horizons in falls prevention. *Age Ageing* 47, 492–498. doi: 10.1093/ageing/afy059

Lucia, S., Aydin, M., and Di Russo, F. (2023). Sex differences in cognitive-motor dual-task training effects and in brain processing of semi-elite basketball players. *Brain Sci.* 13:443. doi: 10.3390/brainsci13030443

Lucia, S., Bianco, V., Boccacci, L., and Di Russo, F. (2021). Effects of a cognitive-motor training on anticipatory brain functions and sport performance in semi-elite basketball players. *Brain Sci.* 12:68. doi: 10.3390/brainsci12010068

Moher, D., Liberati, A., Tetzlaff, J., and Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Med.* 6:e1000097. doi: 10.1371/journal.pmed.1000097

Moreira, P. E. D., Dieguez, G. T. O., Bredt, S., and Praça, G. M. (2021). The acute and chronic effects of dual-task on the motor and cognitive performances in athletes: a systematic review. *Int. J. Environ. Res. Public Health* 18:732. doi: 10.3390/ijerph18041732

Murphy, A. P., Duffield, R., Kellett, A., and Reid, M. (2016). A comparison of the perceptual and technical demands of tennis training, simulated match play, and competitive tournaments. *Int. J. Sports Physiol. Perform.* 11, 40–47. doi: 10.1123/ijspp.2014-0464

Pang, M. Y. C., Yang, L., Ouyang, H., Lam, F. M. H., Huang, M., and Jehu, D. A. (2018). Dual-task exercise reduces cognitive-motor interference in walking and falls after stroke. *Stroke* 49, 2990–2998. doi: 10.1161/strokeaha.118.022157

Pereira-Pedro, K. P., de Oliveira, I. M., Mollinedo-Cardalda, I., and Cancela-Carral, J. M. (2022). Effects of cycling dual-task on cognitive and physical function in Parkinson's disease: a randomized double-blind pilot study. *Int. J. Environ. Res. Public Health* 19:847. doi: 10.3390/ijerph19137847

Piras, A., Lobietti, R., and Squatrito, S. (2014). Response time, visual search strategy, and anticipatory skills in volleyball players. *J. Ophthalmol.* 2014:189268. doi: 10.1155/2014/189268

Plummer, P., Villalobos, R. M., Vayda, M. S., Moser, M., and Johnson, E. (2014). Feasibility of dual-task gait training for community-dwelling adults after stroke: a case series. *Stroke Res Treat* 2014:538602. doi: 10.1155/2014/538602

Roca, A., Ford, P. R., and Memmert, D. (2018). Creative decision making and visual search behavior in skilled soccer players. *PLoS One* 13:e0199381. doi: 10.1371/journal.pone.0199381

Romeas, T., Chaumillon, R., Labbé, D., and Faubert, J. (2019). Combining 3D-MOT with sport decision-making for perceptual-cognitive training in virtual reality. *Percept Mot. Skills* 126, 922–948. doi: 10.1177/0031512519860286

Sabarit, A., Reigal, R. E., Morillo-Baro, J. P., de Mier, R. J. R., Franquelo, A., Hernandez-Mendo, A., et al. (2020). Cognitive functioning, physical fitness, and game performance in a sample of adolescent soccer players. *Sustain. For.* 12:245. doi: 10.3390/su12135245

Sarmento, H., Anguera, M. T., Pereira, A., and Araújo, D. (2018). Talent identification and development in male football: a systematic review. *Sports Med.* 48, 907–931. doi: 10.1007/s40279-017-0851-7

Sarto, F., Cona, G., Chiossi, F., Paoli, A., Bisiacchi, P., Patron, E., et al. (2020). Dual-tasking effects on static and dynamic postural balance performance: a comparison between endurance and team sport athletes. *PeerJ* 8:e9765. doi: 10.7717/peerj.9765

Schaefer, S., and Scornaienchi, D. (2020). Table tennis experts outperform novices in a demanding cognitive-motor dual-task situation. *J. Mot. Behav.* 52, 204–213. doi: 10.1080/00222895.2019.1602506

Schapschröer, M., Lemez, S., Baker, J., and Schorer, J. (2016). Physical load affects perceptual-cognitive performance of skilled athletes: a systematic review. *Sports Med Open* 2:37. doi: 10.1186/s40798-016-0061-0

Slimani, M., Bragazzi, N. L., Tod, D., Dellal, A., Hue, O., Cheour, F., et al. (2016). Do cognitive training strategies improve motor and positive psychological skills development in soccer players? Insights from a systematic review. *J. Sports Sci.* 34, 2338–2349. doi: 10.1080/02640414.2016.1254809

Smith, D. J. (2003). A framework for understanding the training process leading to elite performance. *Sports Med.* 33, 1103–1126. doi: 10.2165/00007256-200333150-00003

Strobach, T. (2020). The dual-task practice advantage: empirical evidence and cognitive mechanisms. *Psychon. Bull. Rev.* 27, 3–14. doi: 10.3758/s13423-019-01619-4

Suchomel, T. J., Nimphius, S., and Stone, M. H. (2016). The importance of muscular strength in athletic performance. *Sports Med.* 46, 1419–1449. doi: 10.1007/s40279-016-0486-0

Tuena, C., Borghesi, F., Bruni, F., Cavedoni, S., Maestri, S., Riva, G., et al. (2023). Technology-assisted cognitive motor dual-task rehabilitation in chronic age-related conditions: systematic review. *J. Med. Internet Res.* 25:e44484. doi: 10.2196/44484

Van Biesen, D., Jacobs, L., McCulloch, K., Janssens, L., and Vanlandewijck, Y. C. (2018). Cognitive-motor dual-task ability of athletes with and without intellectual impairment. *J. Sports Sci.* 36, 513–521. doi: 10.1080/02640414.2017.1322215

Varillas-Delgado, D., Del Coso, J., Gutiérrez-Hellín, J., Aguilar-Navarro, M., Muñoz, A., Maestro, A., et al. (2022). Genetics and sports performance: the present and future in the identification of talent for sports based on DNA testing. *Eur. J. Appl. Physiol.* 122, 1811–1830. doi: 10.1007/s00421-022-04945-z

Voyer, D., and Jansen, P. (2017). Motor expertise and performance in spatial tasks: a meta-analysis. *Hum. Mov. Sci.* 54, 110–124. doi: 10.1016/j.humov.2017.04.004

Wortman, R. J., Brown, S. M., Savage-Elliott, I., Finley, Z. J., and Mulcahey, M. K. (2021). Blood flow restriction training for athletes: a systematic review. *Am. J. Sports Med.* 49, 1938–1944. doi: 10.1177/0363546520964454

Zhou, Q., Yang, H., Zhou, Q., and Pan, H. (2021). Effects of cognitive motor dual-task training on stroke patients: a RCT-based meta-analysis. *J. Clin. Neurosci.* 92, 175–182. doi: 10.1016/j.jocn.2021.08.009

TYPE Original Research
PUBLISHED 09 February 2024
DOI 10.3389/fspor.2024.1289800

OPEN ACCESS

EDITED BY
Karen Zentgraf,
Goethe University Frankfurt, Germany

REVIEWED BY
Jolande Fooken,
Queen's University, Canada
Ashlesh Patil,
All India Institute of Medical Sciences Nagpur, India

*CORRESPONDENCE
Satoshi Shimegi
shimegi.satoshi.celas@osaka-u.ac.jp

RECEIVED 13 September 2023
ACCEPTED 24 January 2024
PUBLISHED 09 February 2024

CITATION
Nakazato R, Aoyama C, Komiyama T, Himo R and Shimegi S (2024) Table tennis players use superior saccadic eye movements to track moving visual targets.
Front. Sports Act. Living 6:1289800.
doi: 10.3389/fspor.2024.1289800

Table tennis players use superior saccadic eye movements to track moving visual targets

Riku Nakazato[1], Chisa Aoyama[2], Takaaki Komiyama[3], Ryoto Himo[4] and Satoshi Shimegi[1,3]*

[1]Graduate School of Frontier Biosciences, Osaka University, Toyonaka, Osaka, Japan, [2]Graduate School of Medicine, Osaka University, Toyonaka, Osaka, Japan, [3]Center for Education in Liberal Arts and Sciences, Osaka University, Toyonaka, Osaka, Japan, [4]Faculty of Science, Osaka University, Toyonaka, Osaka, Japan

Introduction: Table tennis players perform visually guided visuomotor responses countlessly. The exposure of the visual system to frequent and long-term motion stimulation has been known to improve perceptual motion detection and discrimination abilities as a learning effect specific to that stimulus, so may also improve visuo-oculomotor performance. We hypothesized and verified that table tennis players have good spatial accuracy of saccades to moving targets.
Methods: University table tennis players (TT group) and control participants with no striking-sports experience (Control group) wore a virtual reality headset and performed two ball-tracking tasks to track moving and stationary targets in virtual reality. The ball moved from a predetermined position on the opponent's court toward the participant's court. A total of 54 conditions were examined for the moving targets in combinations of three ball trajectories (familiar parabolic, unfamiliar descent, and unfamiliar horizontal), three courses (left, right, and center), and six speeds.
Results and discussion: All participants primarily used catch-up saccades to track the moving ball. The TT group had lower mean and inter-trial variability in saccade endpoint error compared to the Control group, showing higher spatial accuracy and precision, respectively. It suggests their improvement of the ability to analyze the direction and speed of the ball's movement and predict its trajectory and future destination. The superiority of the spatial accuracy in the TT group was seen in both the right and the left courses for all trajectories but that of precision was for familiar parabolic only. The trajectory dependence of improved saccade precision in the TT group implies the possibility that the motion vision system is trained by the visual stimuli frequently encountered in table tennis. There was no difference between the two groups in the onset time or spatial accuracy of saccades for stationary targets appearing at various positions on the ping-pong table.
Conclusion: Table tennis players can obtain high performance (spatial accuracy and precision) of saccades to track moving targets as a result of motion vision ability improved through a vast amount of visual and visuo-ocular experience in their play.

KEYWORDS
catch-up saccade, moving target, virtual reality, ball sports, table tennis

1 Introduction

In ball sports, such as table tennis and baseball, physical actions, such as ball hitting, are executed and adjusted according to the visual information of the ball moving in three-dimensional space. The motor control based on this information is referred to as visuomotor control. Visuomotor performance is determined by the quality and quantity of the visual motion information, which greatly depends not only on the visual system that processes the visual information but also on the gaze control system that acquires the information. Accordingly, research has investigated whether eye movements used by athletes are superior to those of non-athletes.

The way ballgame players move their eyes to collect information during play is referred to as "gaze behavior", to which head and eye movements contribute (1–4). Various gaze behaviors are performed depending on each ball sport, but basically, they consist of a combination of two representative eye movements: saccade and smooth pursuit (5). Smooth pursuit eye movement enables tracking a moving target smoothly and continuously but has the limitation of the eye movement velocity, where continuous ocular tracking becomes difficult if the target speed exceeds 60 to 70 deg/s. To compensate, the gaze is directed by saccades from the current gaze position to the future target position (3).

In table tennis, eye movement plays a greater role than head movement in gaze behavior when directing the eye toward the ball (4). Furthermore, saccades track the ball since the speed of a ping-pong ball often exceeds the threshold of smooth pursuit (6, 7). When table tennis players track a ball coming toward them, players gaze at the opponent's racket striking the ball and direct their gaze to the ball after the strike (catch-up saccades) (6). Based on the information obtained there, players predict where the ball will land and shift their gaze there before the ball arrives (predictive saccade) (8). Therefore, the spatial accuracy of the saccade determines the quality of the ball motion information, which in turn affects the aiming performance of the racket (6, 8). Thus, better saccade ability is expected to be associated with better play.

Several studies have compared saccade ability between various ball athletes including table tennis and non-athletes, showing that athletes have shorter saccade latency (time from stimulus presentation to saccade onset) than non-athletes (9–11). On the other hand, other studies (12, 13) did not find a difference in saccade latency between such groups. These studies included different types of sports athletes and different measurement conditions, so the cause of the discrepancy in results is unclear. Since almost all studies used stationary stimuli, it is possible that the ball players' potential saccadic abilities were not brought out. Additionally, spatial accuracy (14), which is extremely important for ball players' saccadic performance, has rarely been measured. To clarify this point, saccadic ability not only for stationary targets but also for moving targets should be evaluated at least, and in addition to the saccade onset time, the speed and spatial error at the endpoint, etc., should be comprehensively investigated.

When the visual system is exposed to a specific visual stimulus for a long time or frequently, its detection sensitivity to the exposed stimulus improves through plastic changes called perceptual learning (15). For example, prolonged motion stimulation has been reported to improve perceptual motion detection and discrimination abilities specifically in the stimulated motion direction (16–19). Therefore, ball athletes may have an improved ability to analyze the motion of moving targets they often see during play and to predict their trajectories and future destinations. If so, this may also contribute to the improved spatial accuracy of body movements. Since ball athletes track the ball to obtain accurate information during play, investigating their ball-tracking ability is effective as a powerful probe to derive the visual improvement effect and the influence on physical movement. We focused on table tennis, which provides an overwhelming amount of visual motion stimuli compared to other sports, and the balls are tracked mainly by saccades. The potential advantage of saccadic ability in table tennis players may be revealed by using a ball that moves in the depth direction as seen in normal table tennis scenes.

Therefore, we hypothesized that table tennis players will be better able to analyze the motions of moving targets they frequently see during play and predict their trajectories and future destinations accurately, improving the spatial accuracy of saccades that capture moving targets. This study aimed to verify this hypothesis by comparing the saccade ability between table tennis players and non-athlete controls from the perspective of differences in saccade targets, i.e., moving vs. stationary balls and familiar vs. unfamiliar trajectories for moving balls. We assumed that table tennis players would show a superior saccade ability for moving targets over static targets, and for moving targets, for balls with familiar trajectories over unfamiliar trajectories.

In real table tennis, even if a table tennis expert throws out a ball, it is impossible to repeatedly release the ball under exactly the same conditions (trajectory, speed, and direction). We also needed to generate the motion of a real ping-pong ball and the motion of an unfamiliar ball trajectory at different speeds to assess whether there is a visual experience-dependent visual function improvement effect. In addition, ball tracking without a fixed head in a standing position is not suitable for the purposes of this study. This is because the movement of the head also contributes to the movement of the gaze in no small way and the movement of the head accompanying the disturbance of posture directly causes movement of the eyes. Therefore, we used virtual reality (VR) technology to accurately reproduce the trajectory of a ball in a situation close to an actual table tennis scene and measured the gaze movement due to eye movement by fixing the head.

2 Materials and methods

2.1 Experiment 1: moving ball-tracking task

2.1.1 Participants

Healthy university students who had a history of playing table tennis for three years or more (six male and four female, age: 21.0 ± 1.18 years old) and university students who had no history of playing table tennis or other ball-hitting sports (five male and five female, age: 23.6 ± 3.74 years old) participated in the experiment as the table tennis player (TT) group and control group (Control), respectively. All participants underwent a visual acuity test using a Landolt ring, and all had confirmed binocular or corrected visual acuity of 1.0 deg or better. This study was approved by the Osaka University Human Ethics Committee (16,207) and complied with the standards set by the latest revision of the Declaration of Helsinki, except for registration in the database, and each participant provided written informed consent.

2.1.2 Apparatus

The VR environment was designed on a computer containing an Intel Core i7–7,700 K, 4.2 GHz Processor, and Nvidia Geforce GTX 1080ti graphic card. Its output was connected to the VIVE Pro Eye headset (HTC Corporation, New Taipei City, Taiwan) via a link box (Figure 1A). The head-mounted display (HMD) can provide a resolution of 1,440 × 1,600 pixels (615 PPI) per eye with a refresh rate of 90 Hz and a field of view of 110 deg. The eye tracker built into the VR headset records the ocular movement at 90 Hz with an accuracy of 0.5–1.1 deg (20), and the measured data were stored in the computer storage. The center position of the spherical coordinate for VR was calibrated for each experiment as a room setup using pre-installed software. The gaze position in VR space was calibrated before each experiment using eye-tracking software.

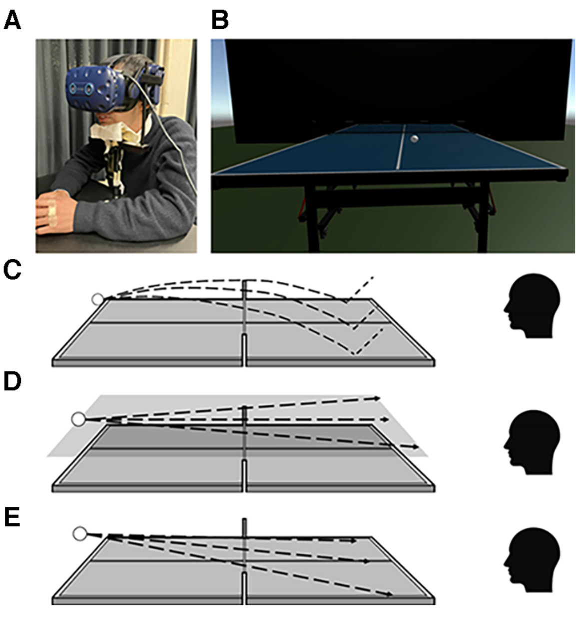


FIGURE 1
Schematic of the experimental setup and experimental conditions. (A) A participant performing a task with his head fixed. (B) Image actually seen by participants. (C–E) Ball trajectories under parabolic (C), horizontal (D), and descent (E) motion conditions.

2.1.3 Visual stimulus

A visual stimulus was created in the VR space using the free software Unity. In the VR space (Figure 1B), a table tennis table (depth × width × height from the ground = 2.76 m × 1.575 m × 0.76 m) was set in front of each participant. The distance between the participants and the front end of the table tennis table was one meter. A black wall was set one meter further away from the far end of the table tennis table.

2.1.4 Task and procedure

In an actual table tennis scene, a saccade is induced immediately after the opponent hits the ball (8). Therefore, the ball-tracking task asked participants to follow with a gaze as much as possible the ball moving from a starting point 30 cm above the far edge of the table tennis table toward the front side. In the task, three types of ball trajectories (parabolic, horizontal, and descent), three types of courses (left, middle, and right), and six speeds were combined to make 54 test conditions.

A parabolic ball motion condition was set as the "familiar ball trajectory" most frequently experienced by table tennis players. The parabolic motion was reproduced according to the data obtained by tracking and recording the movement of the ball, which was fired from a ball-injecting robot consisting of three rotating rotors onto the real table tennis table in the real world (Figure 1C). Next, we set a horizontal motion condition as an unfamiliar trajectory that moves in the horizontal direction with uniform linear motion; this motion does not occur in real table tennis. Under this condition, the ball keeps moving at the same height (30 cm) parallel to the table tennis table (Figure 1D). Finally, the condition for the ball to descend in a uniform linear motion was set as the descent motion condition (similar to a smash but as an unfamiliar trajectory). Here, the ball descends diagonally and linearly toward the points on the table surface which correspond to the bounce points in the parabolic motion condition (Figure 1E). The ball speed range was determined according to the average ball velocity during a rally in an actual table tennis scene (21), and we set the reference speed to be 6.0 m/s. At the reference speed, the arrival time of the ball from the start position to the end position was 0.33 s in the horizontal motion condition. The six-speed conditions (1.2, 2.4, 3.6, 4.8, 6.0, 7.2 m/s) were determined by multiplying the reference speed by the constants 0.2, 0.4, 0.6, 0.8, 1.0, and 1.2, respectively.

The participants sat on a chair with the HMD attached, and their heads were fixed on the chin stand. For this task, the ball was presented at the predetermined starting point on the HMD, started moving 3 s after the ball appearance, and then disappeared just after pausing at the endpoint of each course. The participants were instructed to keep their gaze on the ball presented as accurately as possible and to track it as the ball started to move. The period from the appearance of the ball to its disappearance was regarded as one trial. At the same time as the ball disappeared, a new ball was presented at the start position, and the next trial began with the same sequence. For each trial, the ball's trajectory, course, and velocity conditions were all randomly determined. One set consisted of 10 trials (10 balls), and one block consisted of six sets. The participants were able to rest for about 15 s between task sets. It took about 10 min to complete one block of tasks. To avoid fatigue, a 3-minute rest was provided between the blocks, and a total of six blocks were performed per day (360 balls in total) for 3 days. Participants were verbally asked whether they felt fatigued between blocks and asked if they needed to discontinue the experiment due to fatigue. As a result, no participants asked to cancel or postpone the experiment due to fatigue. Participants observed a total of 1,080 virtual balls, in which 20 trials per condition were conducted. A calibration of the gaze position measurement was performed between sets. The number of practice sessions for the ball-tracking task in Experiment 1 was six sets and was conducted on the first day of the 3-day experiment.

2.1.5 Data analysis

The ball position, eyeball position, and gaze direction in all trials were recorded as coordinate positions and unit vectors. Using the data obtained from the right and left eyes, we analyzed the ball tracking accuracy. Comparisons between groups were made using the average of the right-eye data and left-eye data for each saccade parameter (occurrence rate, onset time, velocity, and endpoint error).

2.1.5.1 Evaluation of ball position and gaze direction

The ball position and gaze direction during the task were determined by calculating the relative angle from a reference vector. The reference vector (horizontal vector) was defined as a vector extending straight and horizontally forward from the center of the eyeball, assuming the situation that the participant was looking straight into the distance without controlling their extraocular muscles. The position data of the ball and gaze were measured separately into horizontal and vertical components and were integrated into a synthetic vector on spherical coordinates with the origin at the center of the eyeball. We defined the gaze direction (G vector in Figure 2A) as the angle θ_1 formed by the gaze direction vector and the reference vector. Similarly, the ball direction (EB vector in Figure 2B) was defined as the angle θ_2 formed between the vector extending from the eyeball to the ball and the reference vector.

2.1.5.2 Evaluation of gaze direction with respect to the ball

To quantitatively evaluate how accurately the gaze was directed at the ball, angle θ_3 formed by the eye-ball vector and the gaze direction vector was regarded as the spatial accuracy of the gaze direction (Figure 2C).

2.1.5.3 Detection and evaluation of saccadic eye movement

The rotation speed of the eye movement was obtained by differentiating θ_1, and the time when the speed of θ_1 became 30 deg/s or more was defined as the saccade onset time. However, if the amplitude of θ_1 was 2 deg or less or the duration was 20 ms or less, it was excluded from the saccade (22). The time when the speed of θ_1 became 30 deg/s or less was defined as the saccade offset time. Angle θ_3 at the end of the saccade was called the saccade endpoint error and was used as an index of the spatial accuracy of the saccade. The smaller the saccade endpoint error, the more accurate the saccadic movement to the ball. Saccade precision (consistency and reproducibility of movements across trials) was calculated as the variation coefficient of the saccade endpoint error.

2.1.5.4 Detection and evaluation of smooth pursuit eye movement

In addition to saccades, participants can follow the ball with smooth pursuit eye movements. Therefore, in trials in which no saccade was observed, eye movements that captured the target within a radius of 2.5 deg of the fovea for more than 90% of the total trial time were defined as smooth pursuit eye movements.

2.1.5.5 Statistical analysis

The occurrence rate, onset time, speed, and saccade endpoint error were statistically analyzed by a two-way ANOVA with the sports group (TT and Control) and ball velocity (0.2, 0.4, 0.6, 0.8, 1, 1.2) as factors. If the interaction was significant, a *post hoc* test was performed for each speed condition using Bonferroni's multiple comparisons. Friedman's test was used to compare the

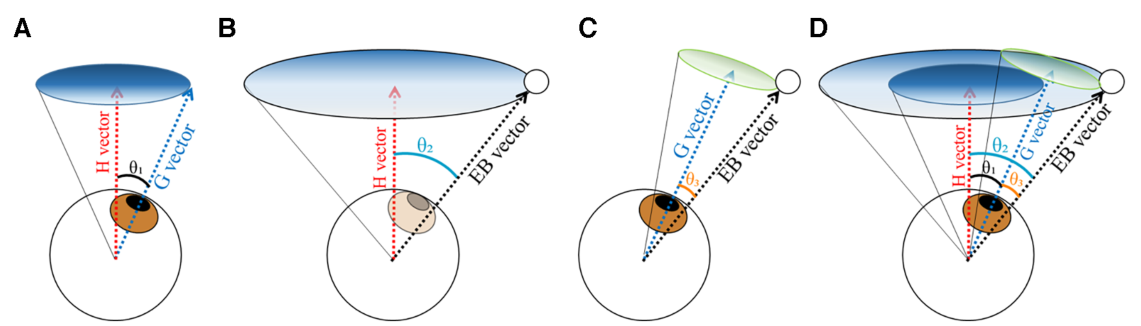


FIGURE 2
Schematic of the analysis of the ball position and gaze direction. (A) Gaze direction. The vector extending straight from the eyeball center perpendicular to the frontal plane was defined as the H vector, and the vector in the direction of the gaze as the G vector. The gaze direction was defined as the angle θ_1 between the G vector and H vector. (B) Ball position. The vector from the eyeball center to the ball center was defined as the EB vector, and the ball position was determined as the angle θ_2 between the EB vector and H vector. (C) Gaze errors. Angle $\theta 3$ between the G vector and EB vector was defined as the gaze error.

variation coefficient of saccade endpoint error between the two groups. The level of significance for all the analyses was less than 5%. All data are expressed as the mean ± standard error.

2.2 Experiment 2: stationary ball-tracking task

2.2.1 Participants

Healthy university students with more than 3 years of table tennis experience (nine male, one female, age: 20.7 ± 2.00 years old) and those who had no history of ball-hitting sports such as table tennis (eight male, two female, age: 21.4 ± 3.10 years old) participated in the experiment as the table tennis player group and control group, respectively. All participants had binocular or corrected visual acuity of 1.0 deg or better. This study was approved by the Osaka University Human Ethics Committee (16,207) and conformed to the standards set by the latest revision of the Declaration of Helsinki, except for registration in the database, and each participant provided written informed consent.

2.2.2 Apparatus and visual stimulus

The experimental apparatus used in this experiment was the same as in Experiment 1. The visual stimulus was also presented in a VR space with a table tennis table and walls as in Experiment 1.

2.2.3 Ball-tracking task

The participants were asked to direct their gaze at a ball appearing at a random position on the table tennis table.

2.2.4 Task procedures

As in Experiment 1, the participants sat on a chair with a HMD and fixed their heads on the chinrest and were instructed to direct their gaze to the ball. In the task, a stationary ball was presented at a random position about 30 cm above the table tennis table. The ball disappeared after being presented for 3 s, and at the same time, the next ball was presented at a random position. One set consisted of 10 repetitions of ball presentation, and one practice set and three test sets were performed. The number of practice sessions for the ball-tracking task in Experiment 2 was one set and was conducted.

2.2.5 Data analysis

As in Experiment 1, angle θ_3 formed by the ER vector and the G vector after the saccade was regarded as the spatial accuracy of the saccade. Data from the right and left eyes were used for the analysis. Comparisons between groups were made using the average of the right-eye data and left-eye data for each index.

2.2.6 Statistical analysis

The saccade error was compared between the table tennis player group and the control group using a one-way ANOVA. The significance level was set to less than 5% for all data. All data are shown as the mean ± standard error.

3 Results

3.1 Experiment 1

In this study, we validated the working hypothesis that table tennis players have superior gaze-tracking ability for a moving visual target by comparing ball-tracking task performance between the TT group and the Control group. Figure 3 presents typical examples of temporal changes in gaze direction and ball position during a trial of the ball-tracking task at a speed of 0.8 for one participant from each group. The TT and Control groups primarily used saccadic eye movements to track the moving ball. The first saccade occurred approximately 300 ms after the ball started to move, directed the gaze to reach the ongoing target (catch-up saccade), and multiple saccades occurred thereafter. Since the start position of the second and subsequent saccades differed depending on the end position of the previous saccade, it was difficult to analyze the spatiotemporal parameters of all other saccades on the same basis. Hence, we analyzed the catch-up saccade observed first in trials when multiple saccades occurred during a trial in this study.

3.1.1 Saccade occurrence rate and smooth pursuit occurrence rate

We investigated the saccade occurrence rate which is defined as the ratio of trials in which at least one saccade occurred to the total number of trials. Figure 4 shows the average saccade occurrence rate of all participants for each group plotted against ball speed. The saccade occurrence rate was analyzed against the ball speed for each trajectory and course (Figure 4). A two-way ANOVA showed that the main effect of ball speed was significant for all trajectories and courses ($p < 0.01$), but that of the group differed depending on the ball trajectory and course. The main effect between groups was significant for the left course of the parabolic motion condition and for the left and center courses of the horizontal motion conditions (left in parabolic: $p < 0.05$; left in horizontal: $p < 0.01$; center in horizontal: $p < 0.01$) but not for the other conditions (center in parabolic: $p = 0.20$; right in parabolic: $p = 0.58$; right in horizontal: $p = 0.14$; left in descent: $p = 0.10$; center in descent: $p = 0.30$; right in descent: $p = 0.70$). A significant interaction was observed for the left course of the parabolic motion condition ($p < 0.05$) and the left course of the horizontal motion condition ($p < 0.01$) but not for the other conditions (center in parabolic: $p = 0.93$; right in parabolic: $p = 0.89$; center in horizontal: $p = 0.29$; right in horizontal: $p = 0.29$; left in descent: $p = 0.20$; center in descent: $p = 0.36$; right in descent: $p = 0.86$). The post-hoc tests in conditions where the interaction was significant showed that the TT group was significantly higher than the Control group at a speed of 1.2 ($p < 0.05$) in the left course of the horizontal motion condition and there was no significant difference in the parabolic motion condition at any ball speed including a speed of 1.2 ($p = 0.18$). In the descent motion condition, no significant between-group differences were observed in any course, and no interactions were observed. Thus, the saccade occurrence was found to depend on the ball speed, the

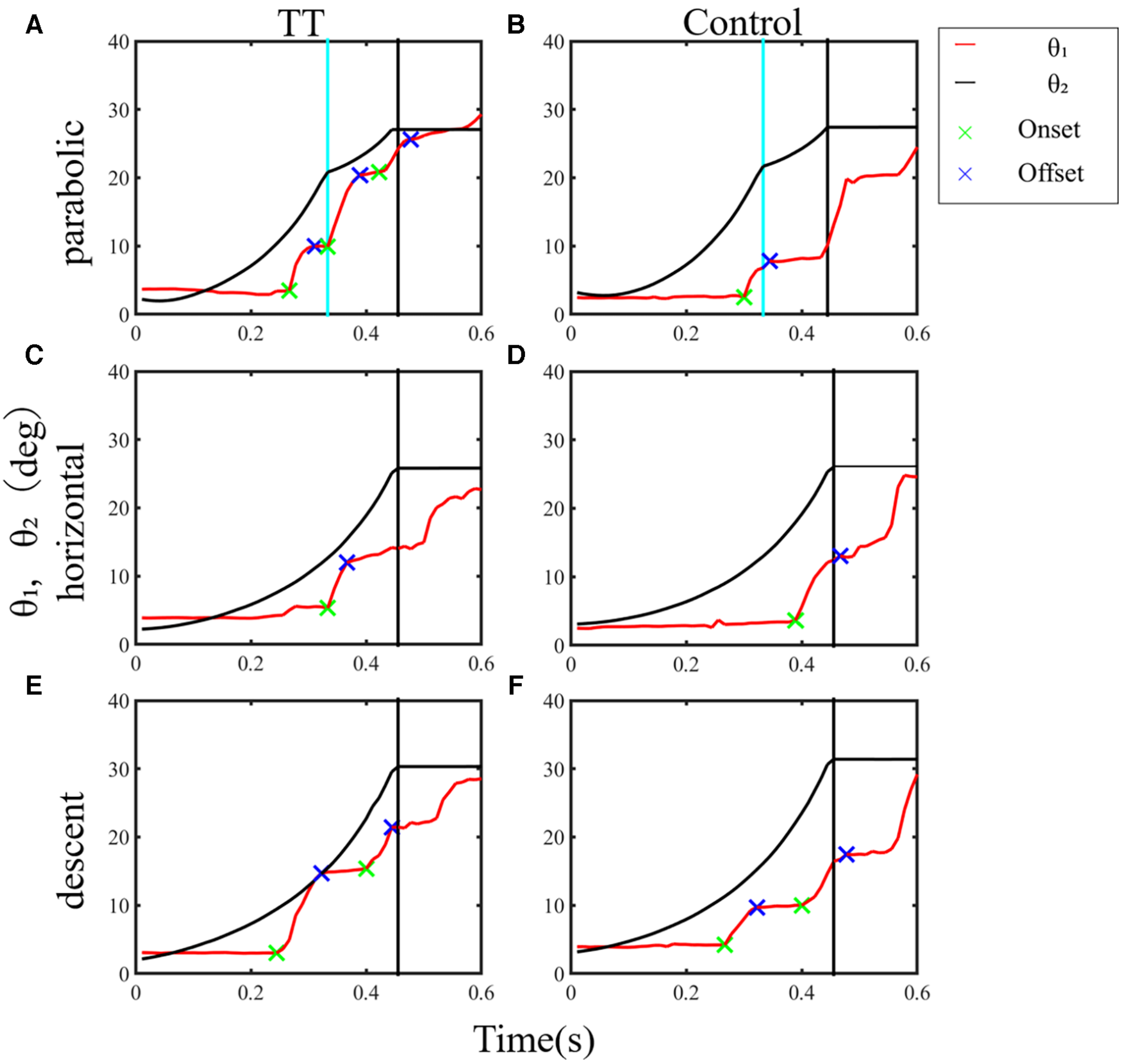


FIGURE 3
Typical examples of temporal changes in the gaze direction and ball position in a trial from a participant for each group. (A) Parabolic motion condition. (B) Horizontal motion condition. (C) Descent motion condition. Redline (θ_1): gaze direction; green and blue cross marks: onset and offset times of the saccade, respectively; blackline (θ_2): ball position; black vertical line: the end of the trial when the ball reached 10 cm from the front edge of the table; pale blue vertical line: time for the ball to contact the table.

course, and the trajectory conditions. In the central course of the horizontal motion condition, the ball moved straight toward the participant's head. Therefore, the eye movement speed required to track the ball was less than 15 deg/s in this condition, although it was more than 20 to 40 deg/s in other conditions. For this reason, the saccade occurrence rate was extremely low compared to other conditions and was detected as an outlier from other conditions by the Smirnov–Grubbs test. Therefore, the central course of the horizontal motion condition was excluded from the following saccade-related analyses in this study.

Since course-dependent differences between groups were observed under the parabolic and horizontal motion conditions only, we compared the saccade occurrence rates for each group between the right and left courses (Figure 5). We found that for the TT group, the saccade occurrence rate was significantly higher on the left course than on the right course in all trajectories ($p < 0.01$), but no interaction with speed was observed. In the Control group, no main effect was observed between the right and left courses, but an interaction was observed for all trajectories (parabolic and horizontal: $p < 0.01$; descent: $p < 0.05$). At the speed of 1.2 in the parabolic motion, the saccade occurrence rate on the left course was significantly lower than on the right course ($p < 0.05$). Thus, the saccade occurrence rate differed depending on the left and right direction of saccades even within the same group, and the left-right difference also differed depending on whether or not the participants had table tennis experience.

The occurrence rate of smooth pursuits was analyzed against the ball speed for each trajectory and course (Figure 4). A two-way ANOVA showed that the main effect of ball speed was significant for all trajectories and courses ($p < 0.01$) but the main effect between groups was not significant (left course in

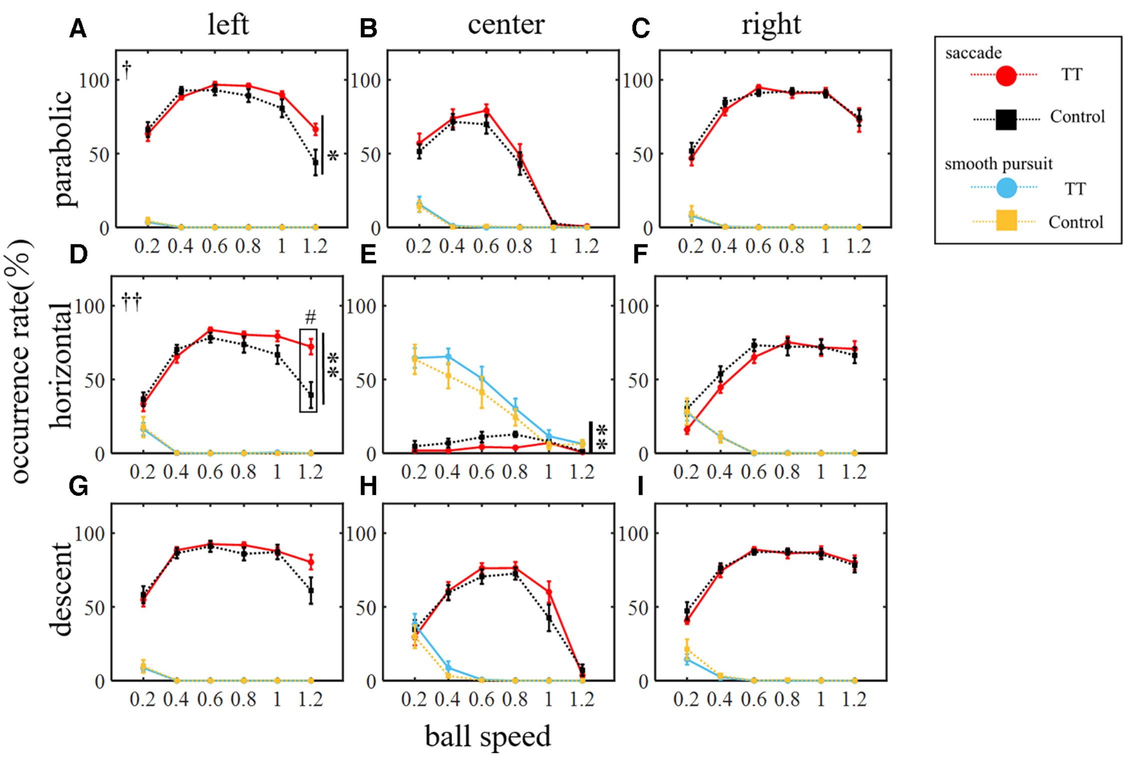


FIGURE 4
Occurrence rate of saccadic and smooth pursuit eye movements. The rows represent the trajectory of the ball: (from top) parabolic motion (A–C), horizontal motion (D–F), and descent motion (G–I). The columns represent the course of the ball: (from left) left (A,D,G), center (B,E,H), and right (C,F,I) courses. Vertical lines with symbols indicate statistical significance between groups. The red and blue circles indicate the TT group and the black and orange squares indicate the Control group. Statistically significant differences in the comparison between the TT and Control groups were observed only for saccades and not for smooth pursuits. ** $p < 0.01$ TT vs. Control, † $p < 0.05$ Interaction, †† $p < 0.01$ Interaction. # $p < 0.05$ TT vs. Control; post-hoc test.

parabolic: $p = 0.74$; center in parabolic: $p = 0.85$; right in parabolic: $p = 0.86$; left in horizontal: $p = 0.92$; center in horizontal: $p = 0.13$; right in horizontal: $p = 0.96$; left in descent: $p = 0.85$; center in descent: $p = 0.22$; right in descent: $p = 0.32$). No significant interactions were also observed (left course in parabolic: $p = 0.99$; center in parabolic: $p = 1.00$; right in parabolic: $p = 1.00$; left in horizontal: $p = 1.00$; center in horizontal: $p = 0.92$; right in horizontal: $p = 1.00$; left in descent: $p = 1.00$; center in descent: $p = 0.71$; right in descent: $p = 0.64$). Thus, the occurrence rate of smooth pursuits did not differ between the TT and Control groups in any condition.

3.1.2 Saccade onset time

The reaction time from the start of the target movement to the generation of the saccade was evaluated as the saccade onset time (Figure 6). The saccade onset time decreased as the ball speed increased irrespective of the ball trajectory or course, reaching about 0.3 s. A two-way ANOVA showed that the main effect of the ball speed was significant for all trajectories and courses ($p < 0.01$) but the main effect of the group was not (left course in parabolic: $p = 0.94$; center in parabolic: $p = 0.64$; right in parabolic: $p = 0.33$; left in horizontal: $p = 0.31$; right in horizontal: $p = 0.54$; left in descent: $p = 0.48$; center in descent: $p = 0.65$; right in descent: $p = 0.11$). Thus, the motor command generation time for saccadic eye movements depended on ball speed, but there was no difference between groups.

3.1.3 Saccade speed

The saccade speed, which is a factor in determining ball tracking performance, increased with ball speed for both the TT group and the Control group regardless of ball trajectory or course (Figure 7). No significant difference was observed in the saccade speed between the two groups across all trajectories and courses (left course in parabolic: $p = 0.82$; center in parabolic: $p = 0.81$; right in parabolic: $p = 0.53$; left in horizontal: $p = 0.85$; right in horizontal: $p = 0.45$; left in descent: $p = 0.14$; center in descent: $p = 0.26$; right in descent: $p = 0.31$; two-way ANOVA). An interaction between the groups and the ball speed was observed only in the center course of the parabolic motion condition ($p < 0.05$). Thus, saccade speed depended on ball speed, but there was no difference between groups.

3.1.4 Saccade endpoint error

The saccade endpoint error was evaluated as the spatial accuracy and increased with increasing target speed in both groups (Figure 8). A two-way ANOVA revealed a statistically

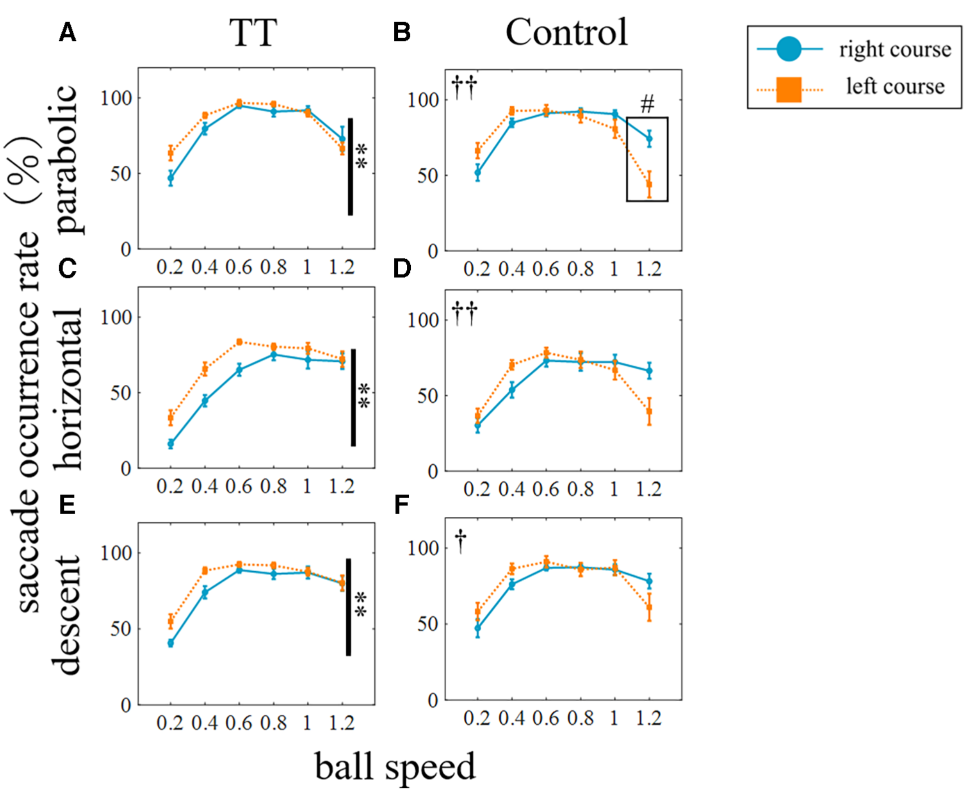


FIGURE 5
Saccade occurrence rates for left and right courses. The rows represent the trajectory of the ball: (from top) parabolic motion (A,B), horizontal motion (C,D), and descent (E,F) motion. The columns represent the group: (from left) TT and Control. The blue circle indicates the right courses, the orange square indicates the left courses. Vertical lines with symbols indicate statistical significance between the right course and the left course. $^{**}p < 0.01$ right course and left course, $^{\dagger}p < 0.05$ Interaction, $^{\dagger\dagger}p < 0.01$ Interaction. $^{\#}p < 0.05$ right course and left course; post-hoc test.

significant difference between the groups depending on the course of the ball but not on the trajectory (left course in parabolic: $p < 0.01$; right in parabolic: $p < 0.05$; left in horizontal: $p < 0.01$; right in horizontal: $p < 0.05$; left, center, and right in descent: $p < 0.01$). No significant interaction was observed (left course in parabolic: $p = 0.64$; center in parabolic: $p = 0.73$; right in parabolic: $p = 0.99$; left in horizontal: $p = 0.10$; right in horizontal: $p = 0.97$; left in descent: $p = 0.76$; center in descent: $p = 0.41$; right in descent: $p = 0.69$; two-way ANOVA). Thus, the saccade endpoint error had little dependence on the ball motion trajectory or course, and the TT group had small error values in all conditions except for the center course of the parabolic motion condition.

The saccade endpoint error was also compared between the right and left courses for each group (Figure 9). The error for the left course was significantly larger than that for the right course in all trajectories for both the TT and Control groups ($p < 0.01$). Post-hoc tests showed significant between-course differences in the TT group for the parabolic trajectory at speeds of 0.8, 1, and 1.2, for the horizontal trajectory at speeds of 1 and 1.2, and for the descent trajectory at speeds of 1 and 1.2.

The TT group repeated saccades to moving targets countless times during their play, so their saccades may not only have higher spatial precision but also greater consistency and reproducibility of movement across trials. Therefore, we investigated the variation coefficient of saccade endpoint error as the precision of saccade (Figure 10). In the parabolic motion condition, the main effect between groups was significant for the left and right courses (left: $p < 0.05$; right: $p < 0.01$; Friedman's test) but not for the central course ($p = 0.46$). In the horizontal motion condition, there was no main effect between groups (left: $p = 0.09$; right: $p = 0.11$; Friedman's test). In the diagonal downward motion condition, there was a significant difference between the groups at the center of the course (center: $p < 0.05$; Friedman's test), and no significant difference was observed between the right and left courses (left: $p = 0.94$; right: $p = 0.20$).

This experiment was conducted over three days, so it was necessary to confirm that no learning effects occurred during that time. Since participants performed 20 trials for each condition, we compared the results of saccade endpoint error between the first 10 trials and the second 10 trials for each condition. Neither the TT group nor the Control group were significantly different in their comparisons: for the TT group (left course in parabolic: $p = 0.32$; center in parabolic: $p = 0.68$; right in parabolic: $p = 0.08$; left in horizontal: $p = 0.55$; right in horizontal: $p = 0.32$; left in descent: $p = 0.32$; center in descent: $p = 1.00$; right in descent: $p = 0.09$), and for the Control group (left course in parabolic: $p = 0.13$; center in parabolic: $p = 0.07$; right in parabolic: $p = 0.32$; left in horizontal: $p = 0.55$; right in

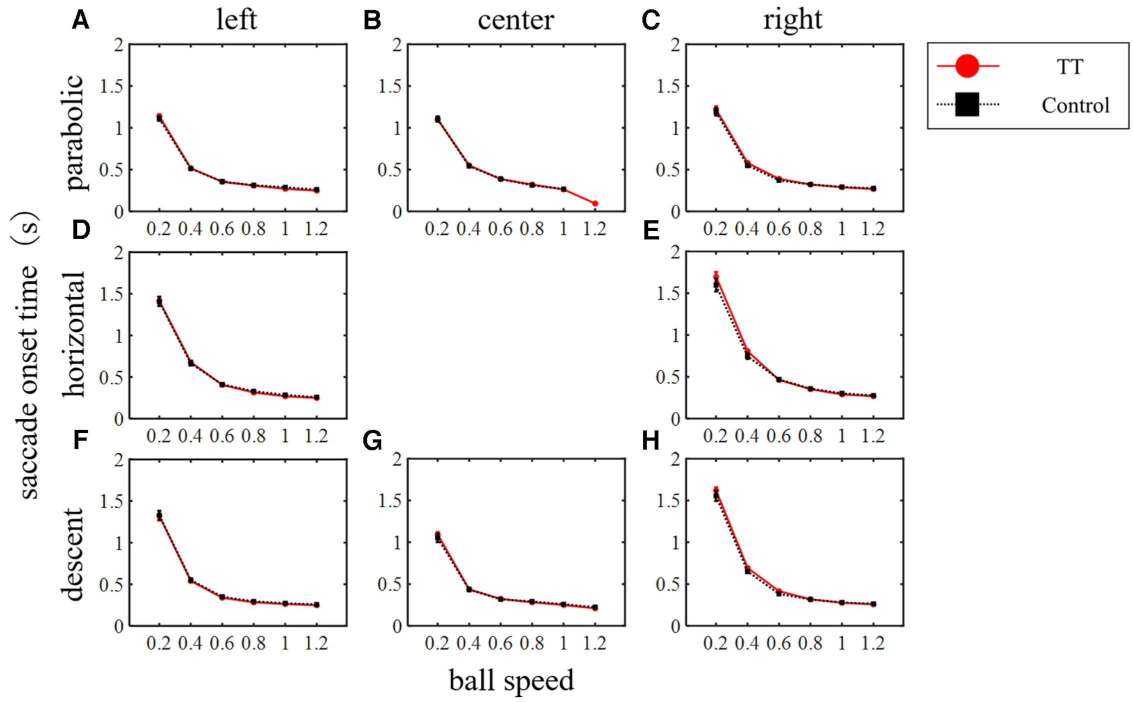


FIGURE 6
Saccade onset time. The main effect of the ball speed was significant in all trajectories and courses ($p < 0.01$) but no difference between groups was observed (two-way ANOVA).

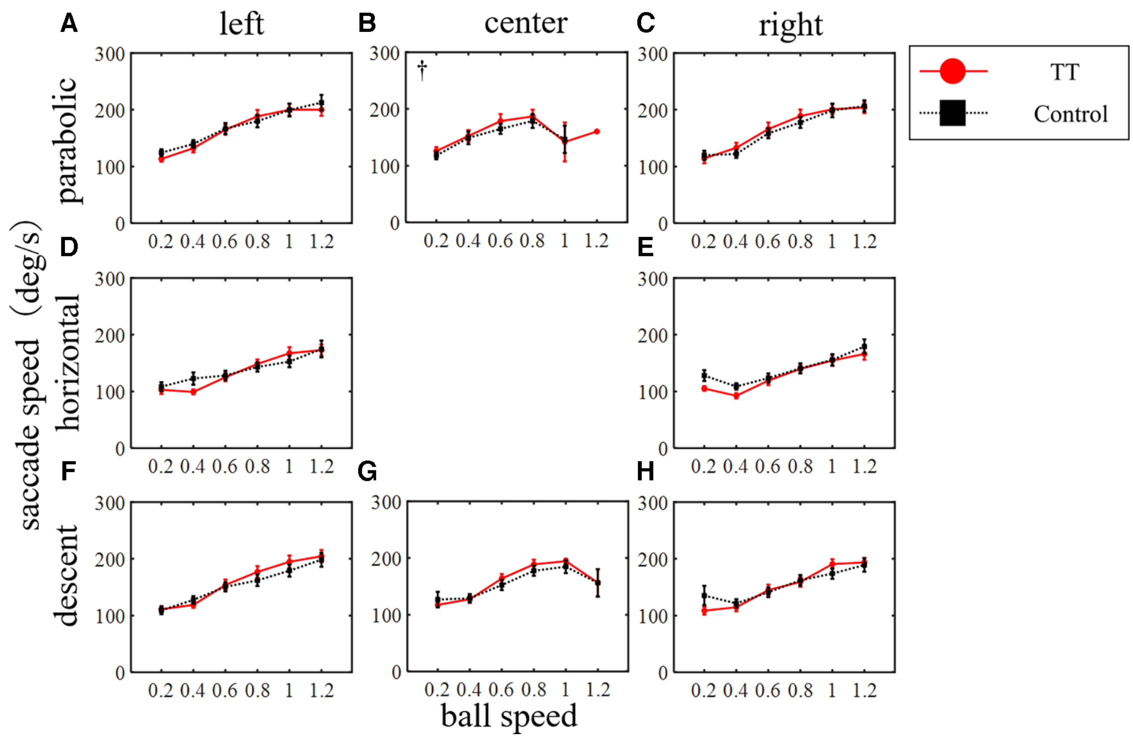


FIGURE 7
Saccade speed. The main effect of the ball speed was significant in all trajectories and courses ($p < 0.01$) but no difference between groups was observed (two-way ANOVA). $^{\dagger}p < 0.05$ Interaction.

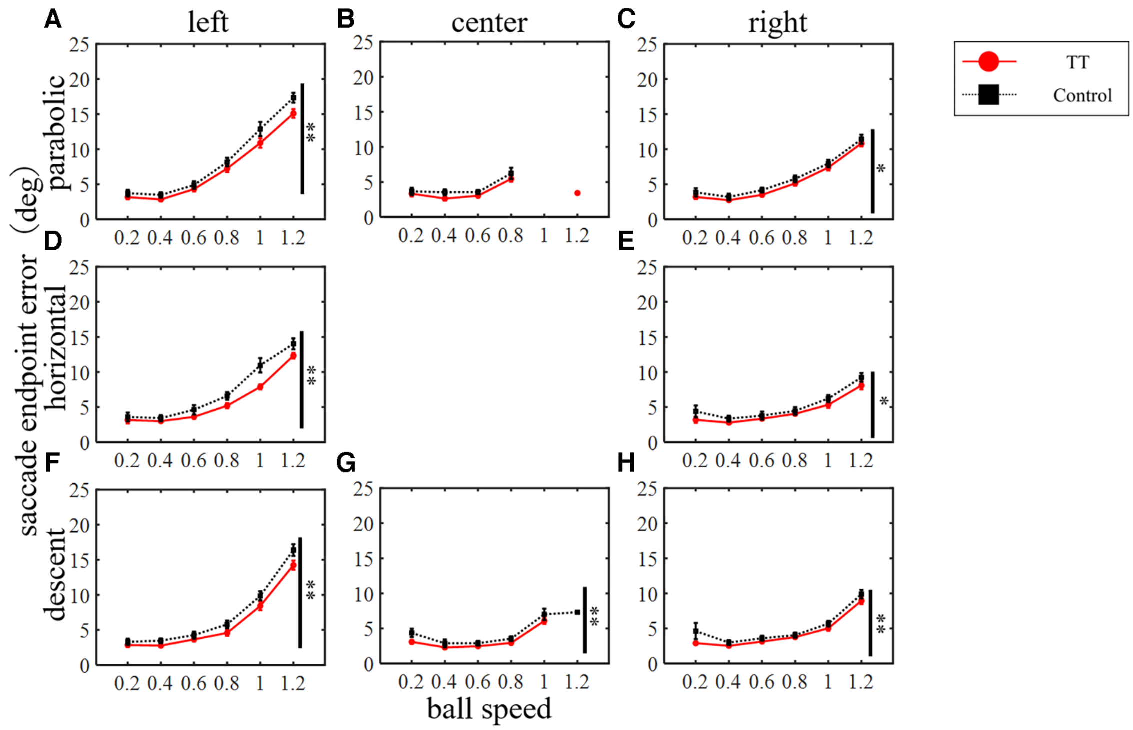


FIGURE 8
Saccade endpoint errors. Vertical lines with symbols indicate statistical significance between groups. *$p < 0.05$ TT vs. Control, **$p < 0.01$ TT vs. Control.

horizontal: $p = 1.00$; left in descent: $p = 0.23$; center in descent: $p = 0.35$; right in descent: $p = 0.57$).

3.2 Experiment 2

Experiment 1 showed that the TT group saccades had better spatial accuracy for moving targets. This finding suggests that table tennis players may have a better ability to predict the future position of the ball and/or better oculomotor control to execute saccades to the predicted position. Saccades to a moving target are thought to require information processing of both the position and motion velocity of the target at a certain point in time. Therefore, to understand which information processing of the saccade system is superior, we examined the saccade ability for stationary targets, which do not require motion information processing. We measured the endpoint error and onset time of saccades to stationary targets presented at random positions 30 cm above the table tennis table (Figure 11). No significant differences between groups were observed for either the saccade endpoint error or onset time (one-way ANOVA). This suggests that table tennis players are better able to predict the future position of the ball.

Additionally, in Experiment 1, the saccade ability for a moving target between the left and right courses was significantly different. Therefore, we analyzed saccades for a stationary target for the left and right directions separately but again found no significant difference in saccade endpoint error or onset time for each group.

4 Discussion

The results of this study are summarized as follows: (1) both the TT and Control groups tracked a ball that began to move from rest using catch-up saccadic eye movements; (2) the TT group had a better saccade ability for moving targets (occurrence rate, spatial accuracy, and inter-trial precision); (3) the superiority of the occurrence rate of the TT group was observed only in the high ball speed range on the left course; (4) the TT group had a high precision of the saccade endpoint error in the parabolic trajectory; and (5) the TT group had no superiority for saccades to stationary targets. These results support our hypothesis that table tennis players have a superior ability of saccades to capture moving targets as a result of stimulus-specific improvements in motion vision by observing the ball's myriad movements.

4.1 Superior ball-tracking ability with saccadic eye movements highlights the importance of saccadic gaze behavior in table tennis

Studies on gaze behavior in table tennis players have shown that they focus on the ball immediately after contact with the racket of the opponent (8, 23, 24). It is where the ball's destination is most uncertain because subtle changes in the angle of the racket surface have a large effect on the direction of the ball's travel, and speed and trajectory also change dramatically.

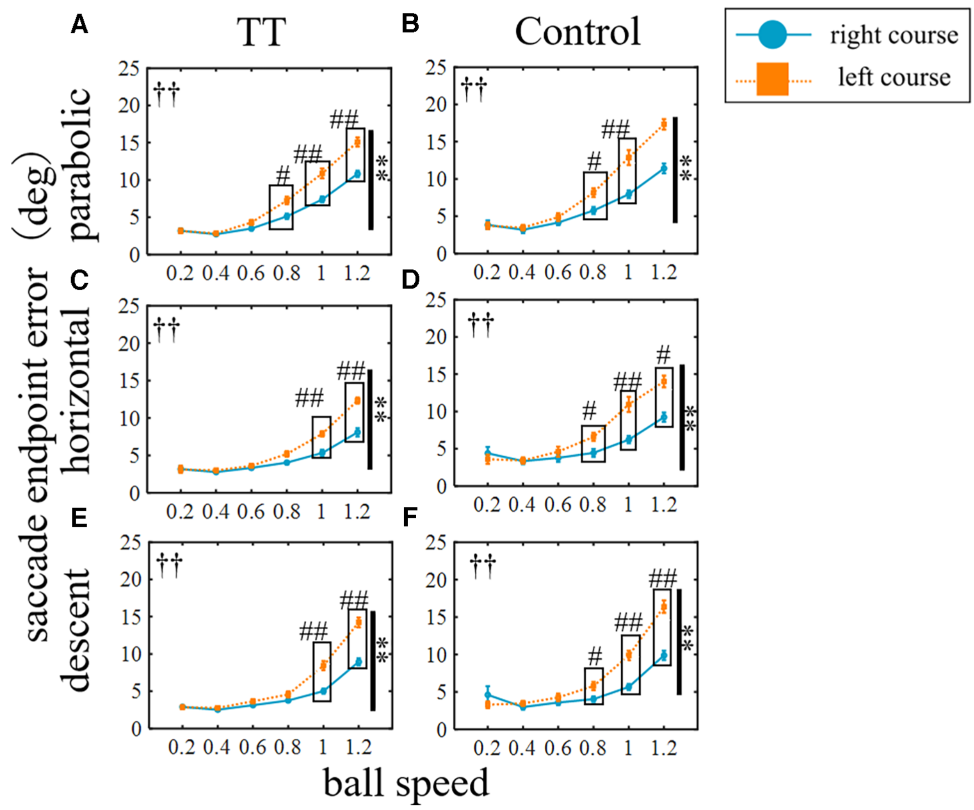


FIGURE 9
Saccade endpoint errors for left and right courses. The blue circle indicates the right courses, the orange square indicates the left courses. Vertical lines with symbols indicate statistical significance between the right and left courses. $^{**}p < 0.01$ right course vs. left course, $^{\dagger\dagger}p < 0.01$ Interaction. $^{\#}p < 0.05$ right course vs. left course, $^{\#\#}p < 0.01$ right course vs. left course; post-hoc test.

Table tennis players' actions begin with quickly and accurately determining the direction and speed of the ball struck by their opponent, and the first part of the ball's trajectory is visually tracked (23, 24). The task in this study mimics this situation.

The gaze behavior of directing one's gaze to where the ball is released has been observed not only in table tennis but also in sports to intercept high-speed balls, such as baseball (25) and cricket (26, 27). Batters in these sports are under severe time constraints and must plan the appropriate motor response based on visual movement information as early as after the ball release to secure time for batting movements (8). It is known that tracking the released ball with a smooth pursuit improves ball prediction accuracy (28, 29) and interception accuracy (30, 31). Consistent with this, it has been reported that expert baseball and cricket players use smooth pursuit to look at the ball released for longer periods than unskilled players (26, 32, 33). The ball-tracking by smooth pursuit is useful in sports where pitchers have limited directions in which to throw (e.g., toward the home plate or wicket). This is because the eye and head movements with a large angular velocity are not required to track the ball immediately after it has been pitched (4). However, in the case of table tennis, where high-speed balls are launched in various directions from an opponent approximately 3 meters away, saccades are essential, as high-speed eye movements are required that go beyond the tracking ability of smooth pursuit. Supporting this, not only the control group but also the table tennis players tracked the ball using saccades in this study. Therefore, ball-tracking through saccades is essential in table tennis, and its spatial accuracy is assumed to contribute to hitting performance.

In sports where the ball bounces, such as table tennis or cricket, saccades are used to direct the gaze ahead of the ball to the point where it is expected to bounce (8, 23, 24, 26). Land et al. (2000) compared skilled and unskilled cricket batsmen and reported that the higher-level batsmen made earlier and more accurate predictive saccades. This means that skilled experts can use the information obtained immediately after ball release to predict bounce events more accurately and in advance. In this study, table tennis players could make saccades with high spatial accuracy to a ball that started moving from their fixation point. This suggests that, like expert cricket players, table tennis players can better analyze the motion of their moving targets and predict where they will reach in the future.

Table tennis players make several saccades to track the ball when the ball speed is low (8). Multiple saccades were also observed at low ball speeds in this study, but at medium to high ball speeds (0.8, 1, 1.2), there is not much time to generate a second saccade. In such situations, the striking performance of players depends on whether or not they can generate saccades based on visual information

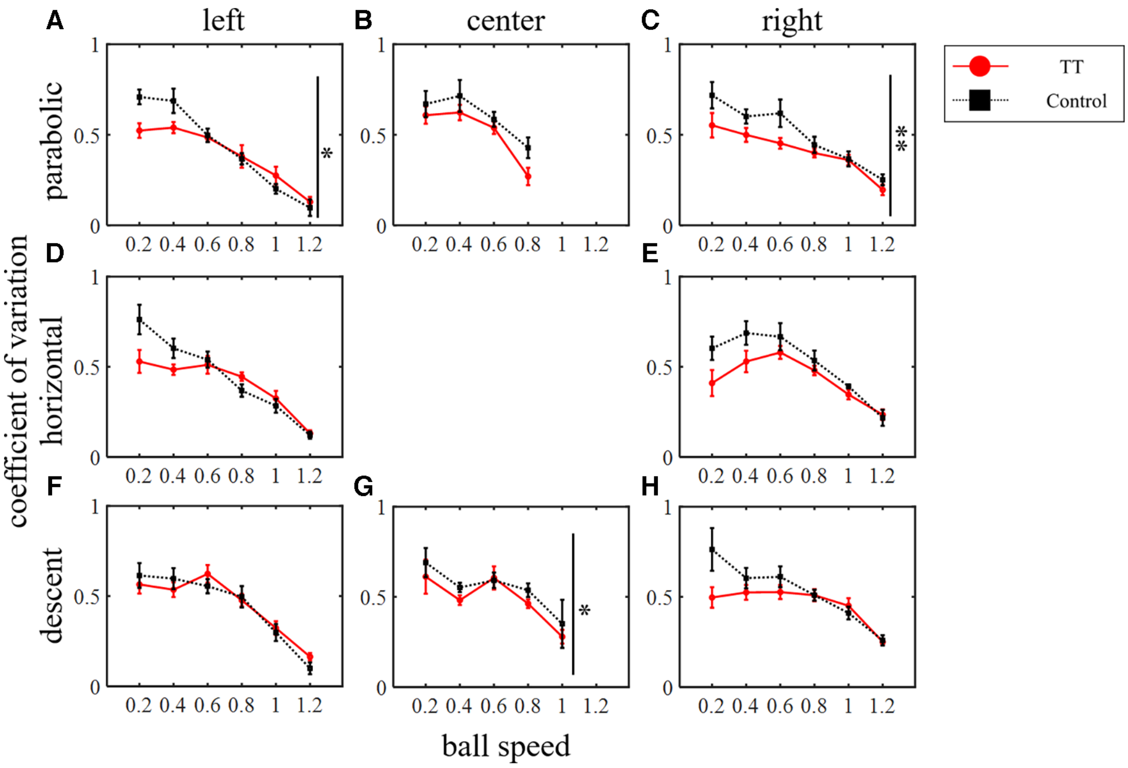


FIGURE 10
The coefficient of variation of saccade endpoint error. Vertical lines with symbols indicate statistical significance between groups. *$p < 0.05$ TT vs. Control, **$p < 0.01$ TT vs. Control.

immediately after the opponent's striking, and whether they can generate saccades with high accuracy. The table tennis players in this study showed superiority in occurrence rate and spatial accuracy of saccades even in the ball high-velocity range, suggesting that these abilities are required in table tennis and that they can be improved through table tennis itself as training.

Saccades quickly shift the eyes to a new location with limited online movement control. Therefore, if there is a deviation in the arrival of a saccade to the target point, it is known that a corrective saccade will follow (34). However, it has been reported that the corrective saccades change the speed perception and arm's intercept action to a moving target depending on the saccade direction (35), which is expected to have undesirable effects on athletes. Therefore, improving the saccadic ability attracted by this study, namely, the incidence and spatial accuracy of saccades occurring after an opponent strikes, will lead to improved striking performance in table tennis.

4.2 The superior saccade ability of table tennis players may reflect the superiority of brain information processing pathways relevant for moving targets

Notably, the TT group showed a superior saccade ability to track moving targets, but the two groups had comparable saccade ability to track stationary targets. This result suggests that the repeated experience of saccade-tracking a fast-moving ball during table tennis trained the associated saccade-generating mechanism and induced plastic changes. The repetitive practice of skill-specific body movements is very effective in acquiring and improving specific motor skills in sports, and the plastic reorganization that occurs in the neural circuits used during this repetition that essential for the improvement (22). Similarly to general motor skills, eye movement ability undergoes plastic changes with practice (36, 37). For example, Dyckmank and McDowell (38) investigated the effect of training on three different eye movement tasks (antisaccade, prosaccade, and fixation) and found that antisaccade performance was improved by antisaccade training, prosaccade task diminished antisaccade performance, and fixation training did not affect antisaccade performance. Therefore, the direction and strength of the training effect on each type of eye movement will differ depending on the type and content of the training to be undertaken. The effect of training on eye movement has been attributed to different cerebral cortical regions and neural circuits for different types of saccades (39, 40). These previous studies suggest our observations are the result of changes in specific brain regions caused by playing table tennis.

In humans (41), the middle temporal complex (MT) of the dorsal visual pathway in the cerebral cortex processes visual motion information and supplies motion signals to various

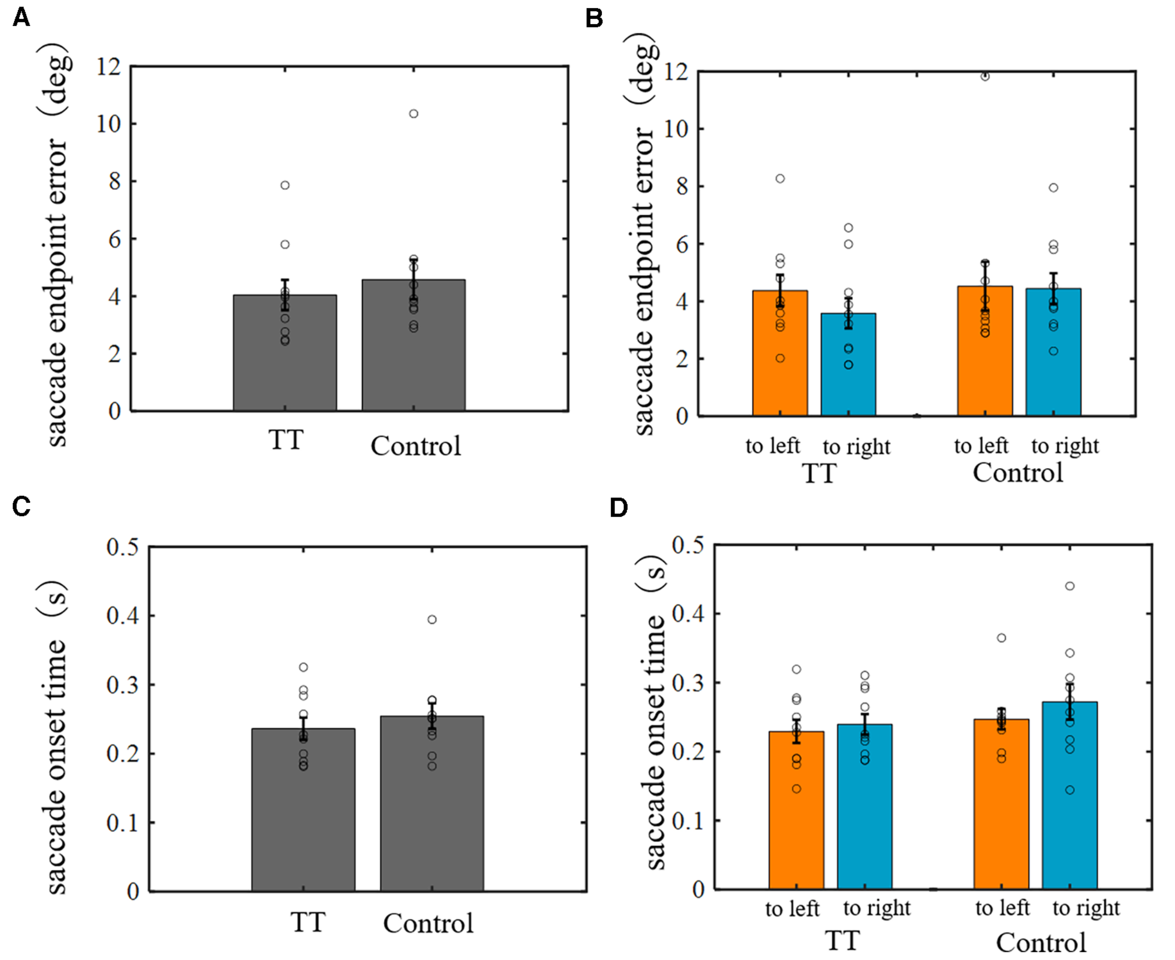


FIGURE 11
The endpoint error and onset time of saccades to stationary targets. (A,C) Comparison between groups. (B,D) Comparison between saccade directions in each group. No significant differences were found in either endpoint error or onset time between groups or saccade directions.

networks that require target motion information. In monkeys (42), disruption of the MT by ibotenic acid impairs pursuit and saccades against moving targets, resulting in large saccade endpoint errors. However, saccades to stationary targets were not affected by this lesion, indicating that both target position detection and saccadic motor control for accurate landing on the target were intact. The loss of the MT impaired motion information processing, compromising the accuracy of the saccade amplitude estimation. In humans too, the accuracy of motion information processing in the MT contributes to the spatial accuracy of the saccade for the moving target (43).

Human and monkey studies have reported that activity in the MT is closely related to the velocity of moving targets. For example, the reaction time required to detect a target motion and initiate body movement decreases non-linearly with increasing target motion speed. Consistent with this relationship, the latency of neuron-related magnetic response in the occipitotemporal region, including the human MT, also shortens non-linearly with increasing target movement speed (44). Similar properties have been reported for the response latency of the N2 component of the motion-evoked potential recorded in the human MT, which is thought to reflect information processing related to motion perception (45). These previous findings indirectly suggest that a shortened response latency in the human MT leads to a shortened physical response time. Similar results were also observed in the present study, where the onset time of the saccade eye movement decreased non-linearly with increasing target movement speed. Since the visual information to generate a saccade in response to a moving target is 100 ms before the start of the saccade (46), we calculated the angular velocity from data 100 ms before the onset of the saccade. For parabolic motion, target motion speeds of 0.2, 0.4, 0.6, 0.8, 1, and 1.2 corresponded to approximately 20, 36, 42, 69, 97, and 121 deg/s, respectively. Similarly, for the horizontal motion condition they were 24, 30, 33, 42, 53, and 61 deg/s, respectively, and for the descending motion they were 17, 16, 30, 42, 57, and 78 deg/s, respectively. Kawakami et al. (44) measured magnetoencephalographic (MEG) neural responses in the occipitotemporal region to the motion initiation of light over a wide range of velocities (0.4–500 deg/s) in humans and measured the physical reaction time. Both the reaction time and MEG response latency were inversely proportional to the target velocity. In particular, significant shortening occurred between target velocities of 0.4 and 30 deg/s. A similar target velocity-MEG response latency function was also reported by Maruyama et al. (2002) (47). In the present study, a significant reduction in the saccade onset time was observed for velocity conditions between 0.2 and 0.6 for all ball trajectories, which approximate 2–30 deg/s. This result agrees with the relationship between the body's reaction time and target motion speed in previous studies (48, 49). Considering the results of Kawakami et al. (2002) and Maruyama et al. (2002), the motion information in the human MT may be used not only for physical reactions, such as button pressing, but also for catch-up saccades, and the information provision speed may be a temporal rate-limiting factor for visuomotor responses.

The superiority of the saccade spatial accuracy (endpoint error) by the TT group may be linked to the human MT. In both groups, the error increased non-linearly when the ball speed increased above the condition of 0.6. Between speeds of 0.6 and 1.2, the ball velocity increased from about 30 deg/s to 100 deg/s. It is known that neurons in monkey MT have tuning properties for motion target velocity, with most neurons exhibiting optimal responses at a velocity of 4–16 deg/s (50, 51). An fMRI study showed that neurons in the human MT have an optimal response of 7–30 deg/s (52). Therefore, the target speed-dependent increase in endpoint error observed in the present study at velocity conditions of 30 deg/s or higher is possibly due to inaccurate information provision by exceeding the optimal motion velocity condition for the motion analyzer in the human MT. If so, the superiority of the saccade spatial accuracy (endpoint error) in the TT group in the high-speed condition was possibly brought about by an improved motion analysis ability in the human MT. Since a motor command of the saccade to the moving target cannot be generated without motion information of the target, the decrease in the rate of the saccade occurrence rate in high-speed conditions on the left course might be due to the same reason. Further research on this point is needed.

4.3 Exposure experience with visual motion stimulation during table tennis may have improved the visual system of the players

Table tennis players are exposed to visual motion stimuli at high frequency and for long periods. When the visual system is exposed to a specific visual stimulus for a long time or frequently, its detection sensitivity to the exposed stimulus improves through plastic changes called perceptual learning (15). It has been reported that prolonged motion stimulation improves perceptual motion detection and discrimination abilities (16–19). Therefore, table tennis players may have an improved ability to analyze the motion of moving targets, which contributes to the superiority of the saccade ability observed in this study. Learning effects in perceptual learning are known to be specific to the exposed stimulus (15), and the above-mentioned improvement effects on perceptual motion detectability and discriminability are specific to the exposed stimulus direction (16, 17).

The superiority of the saccade spatial accuracy of the TT group was observed not only for parabolic trajectories, which are commonly seen in table tennis rallies, but also in the horizontal and descent motion trajectories, which have no equivalent in table tennis rallies. However, we believe that our results are consistent with the stimulus specificity of perceptual learning. In previous studies, learning effects were observed even when the motion direction of the exposed stimulus was shifted by 45 degrees (16, 17). We calculated the angular difference until a saccade occurred for the parabolic motion trajectory, horizontal motion trajectory, and descending motion trajectory in this study; we found that it was only about 5 deg of the visual angle. Therefore, the learning effect caused by the most frequently seen parabolic motion may have affected other motion trajectories as well.

We found that the occurrence rate and spatial accuracy of saccades to moving targets differed depending on the course of the ball, that is, the direction of the saccade eye movement. The saccade endpoint error was significantly smaller in the right course than in the left course in both the TT group and Control group, and the difference was particularly marked at high ball speeds (see Figure 9). Such differences were not observed for other saccade parameters, and no difference was observed in rightward and leftward saccades to a stationary target, so it is unlikely to be an artifact in the measurements. It has been reported that humans have a direction-dependent bias of saccade movement. For example, when saccades were performed in the right and left directions, the onset latency was significantly longer in the left direction (53, 54). Interestingly, the reports showed that the bias was observed in right-handed individuals. There are also reports of a relationship between asymmetry and eye dominance (55). In our study, we did not precisely investigate participants' handedness and eye dominance, so the relationship between saccade lateralization bias and handedness is unclear. Another possible reason for the course difference is attention. The perceptual motion direction discriminability for the coherent motion has been reported to decrease due to divided attention, which was observed only in the left visual field, but not in the right one (56). In the present study, the participants were required to follow moving targets under 54 conditions, so it was necessary to fully utilize their attentional functions due to the high degree of uncertainty. Even small reductions in attention may decrease the generation and spatial accuracy of saccades (57). Finally, the directional bias of the saccade in daily life may be the cause. Reading horizontally written Japanese text needs a rightward saccade which is not just a saccade to a static target, but a predictive saccade that takes context into account, and has aspects in common with saccades to a moving target. The poor ability to saccade to the left in the control group may have been improved in the TT group by the repetitive leftward saccades during table tennis. Further investigation is required to clarify these points.

4.4 Table tennis players with better precision in saccade endpoint error hold a notable advantage in table tennis

The ability to track the ball via saccadic eye movements can be assessed not only with accuracy, defined as an absolute spatial error but also precision (or low inter-trial variability), as noted by Guthrie in 1952 (58). This study found that, specifically in parabolic motion conditions, the TT group exhibited significantly better precision in saccade endpoint error for both left and right courses compared to the Control group. This implies consistent precision in saccade execution. While trial-to-trial variation aids in learning new motor skills, it hampers reaching/interception performance (59). Hence, table tennis players with better precision in saccade endpoint error hold a notable advantage in table tennis with continuous saccades. Van Beers RJ and colleagues (2007) explored the factors influencing variation in human saccadic eye movements, identifying uncertainty in target localization as a primary factor affecting saccade endpoints (60). Consequently, this suggests a reduced uncertainty in predicting the target's future location among the TT group. Common knowledge in sports suggests that trial-to-trial variability lessens with continued practice (61, 62). The TT group's training outcomes likely reflect perceptual learning from visual exposure to motion stimuli in table tennis, with the most pronounced training effect occurring in frequently encountered parabolic motions.

4.5 Human saccade function is optimized in daily life but may be improved by adapting to higher needs in sports

The reason for no differences in the spatial accuracy of saccades for stationary targets between the two groups also deserves consideration. Since the central fovea of the human retina is small, everyone needs highly accurate saccades for object recognition and spatial recognition in daily life. If a spatial error occurs between the saccade arrival point and the visual target, the error is quickly corrected by motor learning, a phenomenon known as saccade adaptation. In the saccade generation mechanism for stationary targets, such a mechanism is universally present regardless of experience, which may explain the lack of difference. However, this observation does not deny the superiority of saccade ability to stationary targets in athletes, as differences have been observed between athletes and non-athletes for saccades under more complex or advanced spatiotemporal demands (9–11, 13, 63).

A superior saccade function for motor targets plays a very important role in the high performance of table tennis players. Aoyama et al. (64) demonstrated using a continuous visuomotor task that a simulated movement of a racket to a fast-moving target is amended based on the visual feedback information acquired after the saccade ends. They also showed that the spatial accuracy of the saccade determines that of the reaching movement. Accordingly, our results suggest that the improvement of the saccade spatial accuracy leads to better table tennis performance.

4.6 Limitations of this research and prospects

In this research, parabolic motion trajectory was reproduced faithfully in virtual space based on tracking data of a table tennis ball shot onto a table tennis table in real space. As a result, several participants of the TT group commented, "It looks so similar to the ball I see in an actual table tennis situation that almost couldn't help but want to hit it back." Therefore, the superior ball-tracking ability achieved by saccadic eye movements found in table tennis players in this study may contribute to actual table tennis performance but the direct relationship with performance is not clear. Therefore, in future studies, it will be necessary to verify the contribution to performance by evaluating the performance of table tennis players in conjunction with their ball-tracking ability. Furthermore, the reason for the superior saccadic ability of table tennis players may reflect their superior ability to process visual motion information and the ability to predict the future position of a moving target based on visual information. However, in this study, it was not possible to distinguish between them, so future studies will be necessary to separately examine motion vision abilities, such as the ability to detect and discriminate the direction of visual motion, and predictive abilities.

5 Conclusions

We conclude that table tennis players have a higher ability to direct their gaze accurately and precisely at the expected arrival point of a ball moving by a catch-up saccade. The catch-up saccade performance can be improved by visual experience and visuo-ocular training executed in ball sports including table tennis, making it possible to acquire highly accurate visual information constantly, which leads to better sports performance.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by the Osaka University Human Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

RN: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft. CA: Conceptualization, Methodology, Writing – review & editing, Funding acquisition. TK: Conceptualization, Methodology, Writing – review & editing, Funding acquisition. RH: Conceptualization, Methodology, Software, Writing – review & editing. SS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article.

This work was financially supported by KAKENHI (Grant Nos. JP20H04077, 19K22807, 16H01869, and 23H03284 to S.S., JP19K19977 to C.A., and 18H06417 to T.K), the Sports Research Innovation Project (SRIP) grant to S.S., and the JST grant "The Support Pioneering Research initiated by the Next Generation" to R.N.

Acknowledgments

We appreciate the participants for their efforts throughout the study. We also thank Dr. Peter Karagiannis for improving the English of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

1. Bahill AT, Laritz T. Why can't batters keep their eyes on the ball? *Am Sci*. (1984) 72:249–53.

2. Roy JE, Cullen KE. Brain stem pursuit pathways: dissociating visual, vestibular, and proprioceptive inputs during combined eye-head gaze tracking. *J Neurophysiol*. (2003) 90(1):271–90. doi: 10.1152/jn.01074.2002

3. Pallus AC, Freedman EG. Target position relative to the head is essential for predicting head movement during head-free gaze pursuit. *Exp Brain Res*. (2016) 234 (8):2107–21. doi: 10.1007/s00221-016-4612-x

4. Higuchi T, Nagami T, Nakata H, Kanosue K. Head-eye movement of collegiate baseball batters during fastball hitting. *PLoS One*. (2018) 13(7):1–15. doi: 10.1371/journal.pone.0200443

5. Diaz G, Cooper J, Hayhoe M. Memory and prediction in natural gaze control. *Philos Trans R Soc B Biol Sci*. (2013) 368(1628):1–9. doi: 10.1098/rstb.2013.0064

6. Shinkai R, Ando S, Nonaka Y, Kizuka T, Ono S. Visual strategies for eye and head movements during table tennis rallies. *Front Sport Act Living*. (2022) 4:897373. doi: 10.3389/fspor.2022.897373

7. De Brouwer S, Missal M, Barnes G, Lefèvre P. Quantitative analysis of catch-up saccades during sustained pursuit. *J Neurophysiol*. (2002) 87(4):1772–80. doi: 10.1152/jn.00621.2001

8. Land MF, Furneaux S. The knowledge base of the oculomotor system. *Philos Trans R Soc B Biol Sci*. (1997) 352(1358):1231–9. doi: 10.1098/rstb.1997.0105

9. Di Russo F, Pitzalis S, Spinelli D. Fixation stability and saccadic latency in élite shooters. *Vision Res*. (2003) 43(17):1837–45. doi: 10.1016/S0042-6989(03)00299-2

10. Morrillo M, Di Russo F, Pitzalis S, Spinelli D. Latency of prosaccades and antisaccades in professional shooters. *Med Sci Sports Exerc*. (2006) 38(2):388–94. doi: 10.1249/01.mss.0000185661.01802.67

11. Yilmaz A, Polat M. Prosaccadic and antisaccadic performance of the athletes in different types of sports. *Biomed Res*. (2018) 29(3):539–43. doi: 10.4066/biomedicalresearch.29-17-3224

12. Babu RJ, Lillakas L, Irving EL. Dynamics of saccadic adaptation: differences between athletes and nonathletes. *Optom Vis Sci*. (2005) 82(12):1060–5. doi: 10.1097/01.opx.0000192346.84549.6a

13. Lenoir M, Crevits L, Goethals M, Musch JWE. Are better eye movements an advantage in ball games? A study of prosaccadic and antisaccadic eye movements. *Percept Mot Skills*. (2000) 91(6):546. doi: 10.2466/pms.91.6.546-552

14. Zhou J. Differences on prosaccade task in skilled and less skilled female adolescent soccer players. *Front Psychol*. (2021) 12:711420. doi: 10.3389/fpsyg.2021.711420

15. Sagi D. Perceptual learning in vision research. *Vision Res*. (2011) 51 (13):1552–66. doi: 10.1016/j.visres.2010.10.019

16. Watanabe T, Náñez J, Sasaki Y. Perceptual learning without perception is not passive. *Nature*. (2001) 413:844–8. doi: 10.1038/35101601

17. Watanabe T, Naáññez JE, Koyama S, Mukai I, Liederman J, Sasaki Y. Greater plasticity in lower-level than higher-level visual motion processing in a passive perceptual learning task. *Nat Neurosci*. (2002) 5(10):1003–9. doi: 10.1038/nn915

18. Seitz AR, Watanabe T. Is subliminal learning really passive. *Nature*. (2003) 432:36. doi: 10.1038/422036a

19. Shibata K, Sagi D, Watanabe T. Two-stage model in perceptual learning: toward a unified theory. *Ann N Y Acad Sci*. (2014) 1316(1):18–28. doi: 10.1111/nyas.12419

20. Yeh PH, Liu CH, Sun MH, Chi SC, Hwang YS. To measure the amount of ocular deviation in strabismus patients with an eye-tracking virtual reality headset. *BMC Ophthalmol*. (2021) 21(1):1–8. doi: 10.1186/s12886-021-02016-z

21. Yuza N, Sasaoka K, Nishioka N, Matsui Y, Yamanaka N, Ogimura I, et al. Game analysis of table tennis in top Japanese players of different playing styles. *Int J Table Tennis Sci*. (1992) 1:79–89.

22. Matsuo Y, Watanabe M, Taniike M, Mohri I, Kobashi S, Tachibana M, et al. Gap effect abnormalities during a visually guided pro-saccade task in children with attention deficit hyperactivity disorder. *PLoS One*. (2015) 10(5):1–14. doi: 10.1371/journal.pone.0125573

23. Ripoll H, Fleurance P. What does keeping one's eye on the ball mean? *Ergonomics*. (1988) 31(11):1647–54. doi: 10.1080/00140138808966814

24. Ripoll H. Uncertainty and visual strategies in table tennis. *Percept Mot Skills*. (1989) 68(2):507–12. doi: 10.2466/pms.1989.68.2.507

25. Toole AJ, Fogt N. Review: head and eye movements and gaze tracking in baseball batting. *Optom Vis Sci*. (2021) 98(7):750–8. doi: 10.1097/OPX.0000000000001721

26. Land MF, McLeod P. From eye movements to actions: batsmen hit the ball. *Nat Neurosci*. (2000) 3(12):1340–5. doi: 10.1038/81887

27. Croft JL, Button C, Dicks M. Visual strategies of sub-elite cricket batsmen in response to different ball velocities. *Hum Mov Sci*. (2010) 29(5):751–63. doi: 10.1016/j.humov.2009.10.004

28. Brenner E, Smeets JBJ. Continuous visual control of interception. *Hum Mov Sci*. (2011) 30(3):475–94. doi: 10.1016/j.humov.2010.12.007

29. Spering M, Schütz AC, Braun DI, Gegenfurtner KR. Keep your eyes on the ball: smooth pursuit eye movements enhance prediction of visual motion. *J Neurophysiol*. (2011) 105(4):1756–67. doi: 10.1152/jn.00344.2010

30. Cesqui B, Mezzetti M, Lacquaniti F, D'Avella A. Gaze behavior in one-handed catching and its relation with interceptive performance: what the eyes can't tell. *PLoS One*. (2015) 10(3):1–39. doi: 10.1371/journal.pone.0119445

31. Fooken J, Yeo SH, Pai DK, Spering M. Eye movement accuracy determines natural interception strategies. *J Vis*. (2016) 16(14):1–15. doi: 10.1167/16.14.1

32. Mann DL, Spratford W, Abernethy B. The head tracks and gaze predicts: how the world's best batters hit a ball. *PLoS One*. (2013) 8(3):1–11. doi: 10.1371/journal.pone.0058289

33. Sarpeshkar V, Abernethy B, Mann DL. Visual strategies underpinning the development of visual–motor expertise when hitting a ball. *J Exp Psychol Hum Percept Perform*. (2017) 43(10):1744–72. doi: 10.1037/xhp0000465

34. Prablanc C, Massé D, Echallier JF. Error-correcting mechanisms in large saccades. *Vision Res*. (1978) 18(5):557–60. doi: 10.1016/0042-6989(78)90202-X

35. Goettker A, Brenner E, Gegenfurtner KR, de la Malla C. Corrective saccades influence velocity judgments and interception. *Sci Rep*. (2019) 9(1):1–12. doi: 10.1038/s41598-019-41857-z

36. Fischer B, Ramsperger E. Human express saccades: effects of randomization and daily practice. *Exp Brain Res*. (1986) 64(3):569–78. doi: 10.1007/BF00340494

37. Jamadar SD, Johnson BP, Clough M, Egan GF, Fielding J. Behavioral and neural plasticity of ocular motor control: changes in performance and fmri activity following antisaccade training. *Front Hum Neurosci*. (2015) 9:1–13. doi: 10.3389/fnhum.2015.00653

38. Dyckman KA, McDowell JE. Behavioral plasticity of antisaccade performance following daily practice. *Exp Brain Res*. (2005) 162(1):63–9. doi: 10.1007/s00221-004-2105-9

39. Pierrot-Deseilligny C, Rivaud S, Gaymard B, Müri R, Vermersch AI. Cortical control of saccades. *Exp Brain Res*. (1995) 37:557–67. doi: 10.1007/s002210050557

40. Pierrot-Deseilligny C, Ploner CJ, Müri RM, Gaymard B, Rivaud-Péchoux S. Effects of cortical lesions on saccadic eye movements in humans. *Ann N Y Acad Sci*. (2002) 956:216–29. doi: 10.1111/j.1749-6632.2002.tb02821.x

41. Orban GA, Van Essen D, Vanduffel W. Comparative mapping of higher visual areas in monkeys and humans. *Trends Cogn Sci*. (2004) 8(7):315–24. doi: 10.1016/j.tics.2004.05.009

42. Newsome WT, Wurtz RH, Dursteler MR, Mikami A. Deficits in visual motion processing following ibotenic acid lesions of the middle temporal visual area of the macaque monkey. *J Neurosci*. (1985) 5(3):825–40. doi: 10.1523/jneurosci.05-03-00825.1985

43. Takami A, Goya R, Aoyama C, Komiyama T, Kawajiri T, Shimegi S. Daily fluctuations in visual motion discriminability contribute to daily fluctuations in continuous visuomotor performance. *Front Sport Act Living*. (2022) 4:1009763. doi: 10.3389/fspor.2022.1009763

44. Kawakami O, Kaneoke Y, Maruyama K, Kakigi R, Okada T, Sadato N, et al. Visual detection of motion speed in humans: spatiotemporal analysis by fMRI and MEG. *Hum Brain Mapp*. (2002) 16(2):104–18. doi: 10.1002/hbm.10033

45. Hülsdünker T, Ostermann M, Mierau A. The speed of neural visual motion perception and processing determines the visuomotor reaction time of young elite table tennis athletes. *Front Behav Neurosci*. (2019) 13(July):1–13. doi: 10.3389/fnbeh.2019.00165

46. Müri RM, Nyffeler T. Neurophysiology and neuroanatomy of reflexive and volitional saccades as revealed by lesion studies with neurological patients and transcranial magnetic stimulation (TMS). *Brain Cogn*. (2008) 68(3):284–92. doi: 10.1016/j.bandc.2008.08.018

47. Maruyama K, Kaneoke Y, Watanabe K, Kakigi R. Human cortical responses to coherent and incoherent motion as measured by magnetoencephalography. *Neurosci Res*. (2002) 44(2):195–205. doi: 10.1016/S0168-0102(02)00129-3

48. Ball K, Sekuler R. Models of stimulus uncertainty in motion perception. *Psychol Rev*. (1980) 87(5):435–69. doi: 10.1037/0033-295X.87.5.435

49. Hohnsbein J, Mateeff S. The relation between the velocity of visual motion and the reaction time to motion onset and offset. *Vision Res*. (1992) 32(9):1789–91. doi: 10.1016/0042-6989(92)90173-G

50. Rodman HR, Albright TD. Coding of visual stimulus velocity in area MT of the macaque. *Vision Res*. (1987) 27(12):2035–48. doi: 10.1016/0042-6989(87)90118-0

51. Liu J, Newsome WT. Functional organization of speed tuned neurons in visual area MT. *J Neurophysiol*. (2003) 89(1):246–56. doi: 10.1152/jn.00097.2002

52. Chawla D, Phillips J, Buechel C, Edwards R, Friston KJ. Speed-dependent motion sensitive responses in V5: an fMRI study. *Neuroimage*. (1998) 7(4 PART II):86–96. doi: 10.1016/s1053-8119(18)31164-9

53. Pirozzolo FJ, Rayner K. Handedness, hemispheric specialization and saccadic eye movement latencies. *Neuropsychologia*. (1980) 18(2):225–9. doi: 10.1016/0028-3932(80)90068-8

54. Thomas Hutton J, Palet J. Lateral saccadic latencies and handedness. *Neuropsychologia*. (1986) 24(3):449–51. doi: 10.1016/0028-3932(86)90033-3

55. Vergilino-Perez D, Fayel A, Lemoine C, Senot P, Vergne J, Doré-Mazars K. Are there any left-right asymmetries in saccade parameters? Examination of latency, gain, and peak velocity. *Investig Ophthalmol Vis Sci*. (2012) 53(7):3340–8. doi: 10.1167/iovs.11-9273

56. Bosworth RG, Petrich JAF, Dobkins KR. Effects of spatial attention on motion discrimination are greater in the left than right visual field. *Vision Res*. (2012) 52(1):11–9. doi: 10.1016/j.visres.2011.10.004

57. Hodges NJ, Wyder-Hodge PA, Hetherington S, Baker J, Besler Z, Spering M. Topical review: perceptual-cognitive skills, methods, and skill-based comparisons in interceptive sports. *Optom Vis Sci*. (2021) 98(7):681–95. doi: 10.1097/OPX.0000000000001727

58. Guthrie, ER. *The psychology of learning*. New York: Revised Ed Harper Harper & Row (1952).

59. Dhawale AK, Smith MA, Ölveczky BP. The role of variability in motor learning. *Annu Rev Neurosci*. (2017) 40:479–98. doi: 10.1146/annurev-neuro-072116-031548

60. Van Beers RJ. The sources of variability in saccadic eye movements. *J Neurosci*. (2007) 27(33):8757–70. doi: 10.1523/JNEUROSCI.2311-07.2007

61. Deutsch KM, Newell KM. Changes in the structure of children's isometric force variability with practice. *J Exp Child Psychol*. (2004) 88(4):319–33. doi: 10.1016/j.jecp.2004.04.003

62. Cohen RG, Sternad D. Variability in motor learning: relocating, channeling and reducing noise. *Exp Brain Res*. (2009) 193(1):69–83. doi: 10.1007/s00221-008-1596-1

63. Jafarzadehpur E, Aazami N, Bolouri B. Comparison of saccadic eye movements and facility of ocular accommodation in female volleyball players and non-players. *Scand J Med Sci Sport*. (2007) 17(2):186–90. doi: 10.1111/j.1600-0838.2005.00535.x

64. Aoyama C, Goya R, Suematsu N, Kadota K, Yamamoto Y, Shimegi S. Spatial accuracy of predictive saccades determines the performance of continuous visuomotor action. *Front Sport Act Living*. (2022) 3:1–12. doi: 10.3389/fspor.2021.775478

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 19 February 2024
DOI 10.3389/fpsyg.2024.1337878

OPEN ACCESS

EDITED BY
Sabine Schaefer,
Saarland University, Germany

REVIEWED BY
Tetsushi Nonaka,
Kobe University, Japan
Gianluca Amico,
Saarland University of Applied Sciences,
Germany

*CORRESPONDENCE
Vicente Luis-del Campo
✉ viluca@unex.es

RECEIVED 13 November 2023
ACCEPTED 11 January 2024
PUBLISHED 19 February 2024

CITATION
Luis-del Campo V, Morenas Martín J, Musculus L and Raab M (2024) Embodied planning in climbing: how pre-planning informs motor execution.
Front. Psychol. 15:1337878.
doi: 10.3389/fpsyg.2024.1337878

Embodied planning in climbing: how pre-planning informs motor execution

Vicente Luis-del Campo[1]*, Jesús Morenas Martín[1], Lisa Musculus[2] and Markus Raab[2]

[1]Faculty of Sports Sciences, University of Extremadura, Cáceres, Spain, [2]Institute of Psychology, Department of Performance Psychology, German Sport University Cologne, Cologne, North Rhine-Westphalia, Germany

Introduction: The aim of the study is to address embodied planning in climbing. Embodied planning was conceptualized as the interaction between perceptual-cognitive pre-planning and motor execution.

Methods: In an experimental study, 18 climbers were asked to pre-plan a climbing route and to perform the route afterward. During pre-planning, the visual search pattern of climbers was captured using a portable eye tracker. After previewing, they were invited to climb the wall.

Results: Results revealed that holds looked at during pre-planning were used twice as much during route execution than those not looked at. The duration of fixations was longer for holds used than those not used during route execution. The experience of climbers (training years) correlated with visual strategies and climbing performance, such that experienced participants climbed faster and fixated at the holds not used for a shorter time.

Discussion: The visual behaviors of climbers were influenced by their past sensorimotor experiences during route previewing, impacting subsequent climbing performance.

KEYWORDS
embodied cognition, expertise, eye-tracking, visual behavior, movement, climbing

Introduction

Climbing was introduced as a new sport discipline in the Olympic Games in Tokyo in 2020 due to its popularity and professionalization around the world (Künzell et al., 2021). The International Federation of Sport Climbing (IFSC, 2023) differentiates three types of indoor climbing disciplines. Specifically, these are known as 'Lead' (athletes climb secured by a rope, one at a time, on an overhanging route with a 6-min time limit; the aim is to go as high as possible in an individual attempt on a 15 m wall); 'Speed' (secured from above, climbers run up standardized parallel routes; the aim is to be the fastest to reach the top of a 15 m wall); and 'Boulder' (these competitions take place on 4-meter-high walls equipped with safety mats; the aim is to solve the highest number of problems – i.e., routes – on four/five round-dependent boulders, having an initial collective observation time of 2 min without yet attempting to complete the routes). There are also three climbing styles to successfully climb to the top of a route: 'On-sight,' where the climber performs a route without prior knowledge of it; 'Flash,' where the climber completes a climb on the first attempt after receiving guidance on the route; and 'Redpoint,' where the climber completes a route without falling after several unsuccessful attempts, rappelling down the route or interceding with a top rope.

A crucial factor for climbing performance is the development of an efficient climbing style, which entails interactions between the perceptual, cognitive, and motor system (Saul et al., 2019). Recently, the theoretical concept of embodied planning has been put forward, and specific predictions about the motor-cognitive interactions underlying climbing performance have been formulated (Musculus et al., 2021). The present study aims to test embodied planning predictions by particularly focusing on the impact of pre-planning on subsequent motor execution for the 'On-sight' style in indoor climbing (e.g., a climb without previous practice).

In climbing, climbers engage in route previewing before approaching the wall and executing the route. During this phase, climbers take a close look at the layout of the holds and plan which holds to use. After this initial previewing, climbers approach the wall and start climbing the route. In climbing research, experimental studies have examined the effects of route previewing in the initial pre-planning phase on subsequent climbing performance. Previewing is related to successful climbing performance (Sanchez et al., 2012, 2019; Seifert et al., 2017). Climbing studies focusing on pre-planning have used perceptual measures such as visual search behavior (Seifert et al., 2017; van Knobelsdorff et al., 2020), estimations of hold properties (e.g., Bläsing et al., 2014), and estimations of whether holds could be reached or not (e.g., Seifert et al., 2021a). These perceptual measures are then related to the number of holds used or the time needed to execute the route (Nieuwenhuys et al., 2008; Sanchez et al., 2012; Seifert et al., 2017).

From an embodied cognition perspective, the initial or pre-planning during the previewing of a climbing route depends on both the spatial information of specific hold positions and the climbers' action capabilities. This means that the perception of the spatial properties of the environment is scaled to the ability of each performer who will execute the intended movements (Paterson et al., 2013). From this embodied perspective, the climber should not only perceive the spatial location of each hold at the climbing wall but also associate specific opportunities for action based on the sequence of holds available in the specific environment. Therefore, in this study we aim to directly capture the potential effects of the environment by analyzing climbing routes in a fine-grained manner, i.e., by inspecting the functional relation between gaze and movement execution on the level of holds. Furthermore, it has been suggested that climbing expertise produces action capabilities at different skill levels, such that advanced climbers showed greater maximal reaching distances than intermediate climbers. However, no effect of climbing expertise on their calibration accuracy was found because the different expertise groups estimated their maximal reaching distance similarly when this estimation was scaled to their actual maximal reaching distance (Seifert et al., 2021b). Therefore, climbers of all skill levels need to consider their bodily state as well as physical and technical contraints in relation to the environmental structure because their individual action capabilities might affect their visuomotor complexity during pre-planning and execution in on-sight climbing (i.e., the layout of the route, van Knobelsdorff et al., 2020).

Embodied planning explicitly considers these interactions between cognitive and motor planning in climbing. The embodied planning process is a continuous, bi-directional feedback loop. Through this feedback loop, perceptual and cognitive planning processes in the pre-planning phase constantly interact with motor-planning processes occurring during the execution of a plan (Musculus et al., 2021). Therefore, the embodied planning process is constantly influenced by bodily as well as sensorimotor experiences. This means that "what" I plan to do will also affect "how" I do it when executing a task (Raab, 2017). We argue that in planning a complex task such as completing a climbing route, both the "what" and "how" are intertwined (Boschker et al., 2002) as embodied cognition approaches suggest (Raab and Araújo, 2019). We note that pre-planning and execution can be partly experimentally separated – looking at a climbing wall without moving at the wall can be considered as "rather cognitive" or "more cognitive" pre-planning, whereas during climbing, both the "what" and "how" components of embodied planning are more tightly interrelated, with motor and cognitive planning aspects interacting constantly. Importantly, both the "how" and "what" components of the plan as well as the interaction are likely to be influenced by the climbing experience (Sanchez et al., 2019; Musculus et al., 2021). Therefore, the present study tests whether climbers with more experience look for potential routes on the climbing wall and pre-plan climbing routes differently.

The present study

The present study aims to test embodied planning in climbing and to capture the combined visual and motor performance of climbers. This aim will be delivered by exploring whether climbing experience is related to pre-planning the route during route preview and to motor performance during route execution. We envision a better understanding of embodied planning processes and potential effects of experience by analyzing which holds climbers look at during route previewing and which holds they use when climbing the wall (Musculus et al., 2021).

We hypothesized that holds that were fixated on more often and for longer during the pre-planning of the route would be more frequently used when executing the plan in climbing the route. This effect should be accentuated for expert climbers compared to less experienced climbers.

Materials and methods

Participants

A priori power analysis performed with the G*Power 3.1.9.7 software (Faul et al., 2007) was used to calculate the required sample size for this study. The results showed that a minimum sample size of 15 participants were required (settings: paired sample t-test, $d = 0.80$, alpha level = 0.05, power = 0.8). To satisfy this sample requirement, we recruited 18 male climbers (Mage = 26.56 years old, $SD = 4.73$). The sample followed previous climbing studies with gaze measures ($N = 18$ in Seifert et al., 2017; $N = 12$ in Nieuwenhuys et al., 2008). The climbing performance level of the participants' *on-sight* style was between the 18 and 28 levels of the International Rock Climbing Research Association (IRCRA), reporting a scale of 6b + and 8b in the French scale (see Draper et al., 2011, 2015 for a comparison of different grading scales). We also measured their height ($M = 170.53$ cm, $SD = 11.19$), arm span ($M = 176$ cm, $SD = 9.19$), ape index (i.e., the measure of the ratio of an individual's arm span relative to their height; $M = 1.03$, $SD = 0.03$), weight ($M = 68.38$ kg, $SD = 7.38$), maximum specific finger strength of the right hand ($M = 370$ N, $SD = 74.20$), and maximum specific finger strength of the left hand ($M = 378.30$ N, $SD = 82.40$). All participants had a license for climbing competitions. They had accumulated a mean climbing experience of 8.22 years (*SD* = 4.45) and had trained in climbing for 2.94 years (*SD* = 2.96). The frequency of training was 3–4 sessions per week, and each training session lasted at least 1 h. For simplification, we refer to all climbers as "experienced" and test different degrees of experience on pre-planning and climbing behavior in our hypotheses.

Participants voluntarily took part in the study and provided informed consent prior to the start of the experiment. The study was performed according to the ethical standards of research of the university in accordance with the Declaration of Helsinki (2013). Specifically, this study received approval from the Bioethics and Biosecurity Committee on 6 March 2018 (n° 33/2018). Participants received general information about the research contexts and signed an informed consent form, but were naïve to the specific hypotheses.

Materials

Climbing test

In the present study, a tiltable climbing wall was built to reproduce representative situations of boulder climbing championships. This wall in the laboratory was engineered based on (i) the French grading system of difficulty, being most commonly used in mainland Europe, and (ii) competition regulations of the IFSC (2022) (e.g., the routes limiting the risk of falling that result in injuries, no downward jumps required, starting holds/top clearly marked with one color). The design of the climbing wall was supported by advice from five expert coaches of a Regional Mountain and Climbing Federation with more than 10 years of climbing experience. One coach was also an experienced setter in national official climbing competitions. They set the route following some of the boulder rules of the IFSC (2022) with a variety of sizes and shapes, leading to the creation of different climbing routes of medium–low difficulty levels (17 IRCRA level/6b + French scale). Therefore, all participants had the requisite minimum skill level to climb the wall.

The climbing wall contained a total of 21 foot- and hand-holds (footholds: from 1 to 6, and handholds: from 7–9 and 11–21). The best route for climbing was selected by a consensus of the expert coaches, containing a recommended sequence of 13 hand moves, using 10 holds (hand-holds numbers 7, 8, 9, 11, 12, 13, 14, 16, 18, and 21; see Figure 1). A number of alternative hand-holds were added to the wall to disguise which route would be the best for climbing it. For this purpose, some deceptive hand-holds offered a shorter but more complicated route (holds 15, 17, 19, and 20). The experts finally decided collectively the hand-holds needed to be gripped in a correct sequence to complete the best route to climb the wall safely. Altogether, we used a modified bouldering task with more handholds than 12 and the average number of 4–8 handholds per boulder as recommended by the IFSC (2022) to ensure the ability of climbers to visually inspect a boulder before ascent it.

We assessed individual factors that are known to affect climbing performance. First, a TANITA BC-418 bio-impedance scale was used for weight measurement, and a measuring tape was used for height and ape index parameters. Second, a SMEDLEY III hand dynamometer coupled to a wooden base was used for the measurement of the specific strength variable for climbers' fingers. Each climber placed the forearm onto the base and fingers on the dynamometer in the form of a climbing grip (Morenas et al., 2013). Finally, a FANTEC BEASTVISION HD camera was used to record the measurement protocols and the later performance of the climbers on the wall.

Pre-planning (during route previewing)

Visual search behavior

We used a mask-type eye tracker (Morenas et al., 2018) to capture gaze underlying expert performance (Gegenfurtner et al., 2011). Gaze parameters follow previous climbing studies (Nieuwenhuys et al., 2008; Grushko and Leonov, 2014; Seifert et al., 2017): the *number*, *duration*, and *sequence* of visual fixations that each climber performed on the holds of the climbing wall or beyond. In this study, a visual fixation was defined as the minimum time of 100 ms that the gaze remained stable at a location within 1.5° of the visual arc (Williams and Davids, 1998).

We measured the *visual performance* (*VP*) by comparing which of the hand-holds that experts had determined to be the ones to use to complete the route were actually looked at by the climbers. The holds determined by the experts are referred to as "key" holds. For example, if the fixations of climbers matched all hand-holds included on the route designed by expert coaches to climb the wall, then the climber achieved a 100% of *VP*. If they fixated at half of the holds, the value was 50% of *VP*. If they did not fixate their gaze at any of the designed holds, the value was recorded as 0% of *VP*. The climber had to perform at least one fixation on each of the 10 holds proposed by the coaches to achieve the 100% value. The designed route was not known by any of the participants.

Motor execution (during route execution)

Climbers were asked to climb the route that was judged as most suitable to reach the top. We measured the *motor performance* (*MP*) by comparing which of the hand-holds that experts had determined to be the ones to use to complete the route were actually selected and used by the climbers during route execution. Equal to *VP*, *MP* was analyzed as a percentage. For example, if the climbers placed their hands on all hand-holds that were previously determined by the experts, they achieved a 100% for *MP*.

In addition, variables related to climbing performance used in past climbing studies (Nieuwenhuys et al., 2008; Sanchez et al., 2012) were included in the analyses. For example, the total climbing time (*Tclimb*) was the time that the climbers took to complete the climbing wall, being recorded from when they raised both feet off the ground until the moment that they placed both hands on the last hand-hold of the climbing sequence. We also recorded whether the climber completed the route on the wall (*Froute*) and the number of trials needed to complete a route successfully (*Ntrial*).

Procedure

Each participant used his own climbing equipment. After a specific climbing warm-up near to the laboratory, each climber performed the anthropometric and specific finger strength

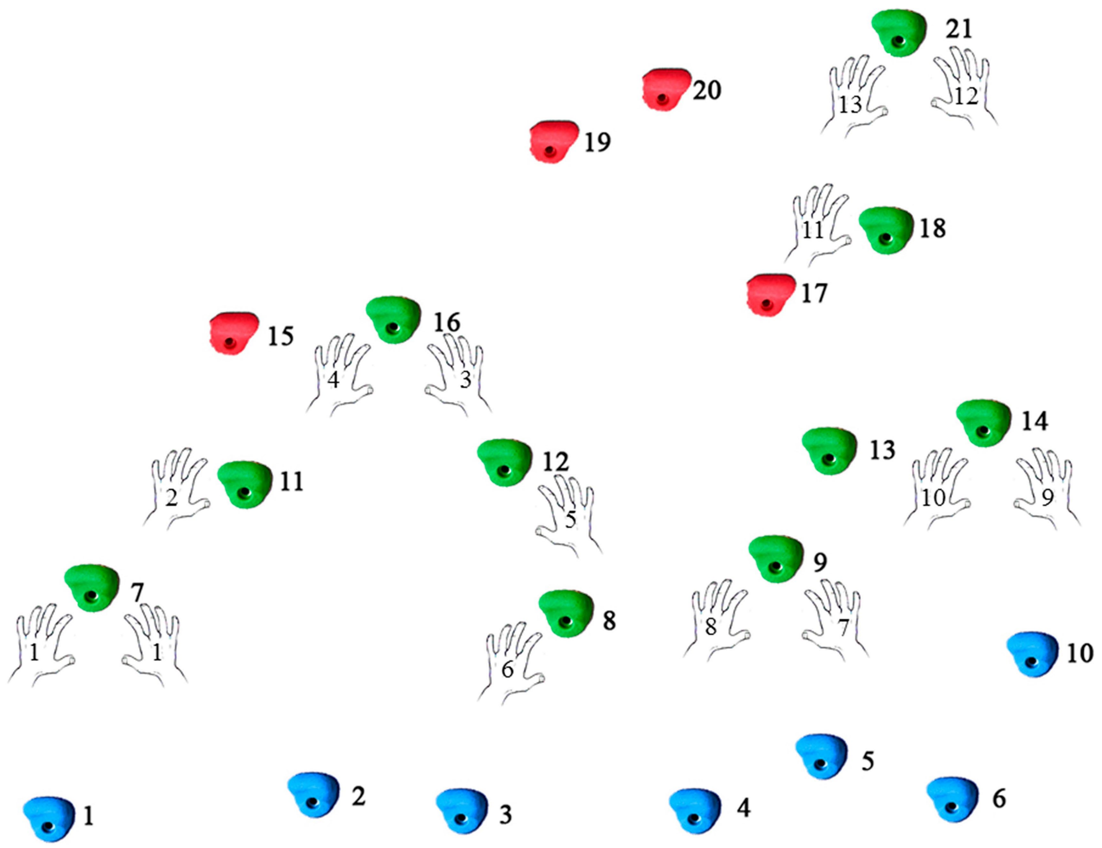


FIGURE 1
Locations of the hand-holds on the climbing wall (numbers 7-8-9-11-12-13-14-16-18-21 for the "key" hand-holds and 15-17-19-20 for deceptive hand-holds proposed by the expert coaches; number 1-2-3-4-5-6-10 for feet-holds).

measurements in a side-room. Then, the climber was directed to the only illuminated area of the room (calibration zone) where the eye-tracking device was attached to the participant's head (Figure 2A).

The participant sat on a stool with a height-adjustable chin rest to look at the projection wall. The calibration protocol began (Figure 2B) with the projection of the nine calibration points, with climbers instructed to view the markers only with eye movements (Figure 2C). When this process finished, the participant stood up with his back to the climbing wall at a distance of 4 m in a delimited area of 1×1 m.

Once there, the lights were turned on, and the participant heard the final instructions: "You must look through the route in front of you as you do in competitions or training sessions. The route starts at the red hold marked on the lower left side and ends in a red hold marked on the upper right." The climber had a maximum of 2 min to observe the boulder before trying to climb it. The researcher (Figure 2D) signaled to turn and look at the route from the delimited area (Figure 2E). After this, the participant was invited to complete the route to the top (Figure 2F). They had several trials to climb the wall although they strived to ascend it at the first attempt.

Statistical analysis

Nonparametric tests were used in this study because the Shapiro-Wilks analysis confirmed that the data of the dependent variables did not display a normal distribution. We performed descriptive statistics to analyze pre-planning regarding the sequence of holds looked at and used (see Figures 3, 4), how often holds were looked at during route previewing, and how often they were used when executing the plan (i.e., route execution). We used the frequency distribution using Chi^2 tests to analyze whether holds that were looked at vs. not looked at were more often used during the execution of the route.

We performed correlational analyses to explore relations between visual performance (*VP*), motor performance (*MP*), other variables related to visual search behavior (e.g., number and duration of fixations on the 21 holds of the climbing wall), and climbing performance (e.g., *Tclimb*, *Froute*, *Ntrial*) during route previewing and route execution. We also analyzed whether visual pre-planning and motor execution in climbing were related to experience (years of training). We did so by using correlational analyses and model fitting, in which we compared a linear, quadratic, and a growth function regarding model fit. Exploratorily, we computed and analyzed conditional gaze entropy following the procedure of Hacques et al. (2021). We did not see any significant relation to our study variables of interest. For interested readers, we added the descriptive statistics for each individual climber to the Supplementary material (please see Supplementary Tables 3, 4 and 5).

An alpha level of <0.05 was set for all analyses. Statistical analyses were performed using the statistical package SPSS 21.0 (© 2012 SPSS Inc.). The Grafos 1.3.5 software was used for the visualization of the sequence of fixations and hand-holds performance made by the climbers.

FIGURE 2
Procedure: Positioning the eye tracker **(A)**. Instructions about calibration process **(B)**. Calibration process **(C)**. Participant receiving instructions **(D)**. Visualization phase **(E)**. Performance phase **(F)**.

Results

To better understand the interplay of pre-planning and route execution in climbing, visual search behavior and motor execution were analyzed. The sequence of visual fixations and motor execution performed by the climbers on the hand-holds of the climbing wall during route previewing and route execution are depicted in Figures 3, 4, respectively. In these Figures, we observe that four of the 10 "key" hand-holds (holds 7, 11, 16, and 21) were looked at for longer times and used more often. For example, hold 16 was fixated at for approximately 27 s by the climbers and grasped 18 times during climbing execution.

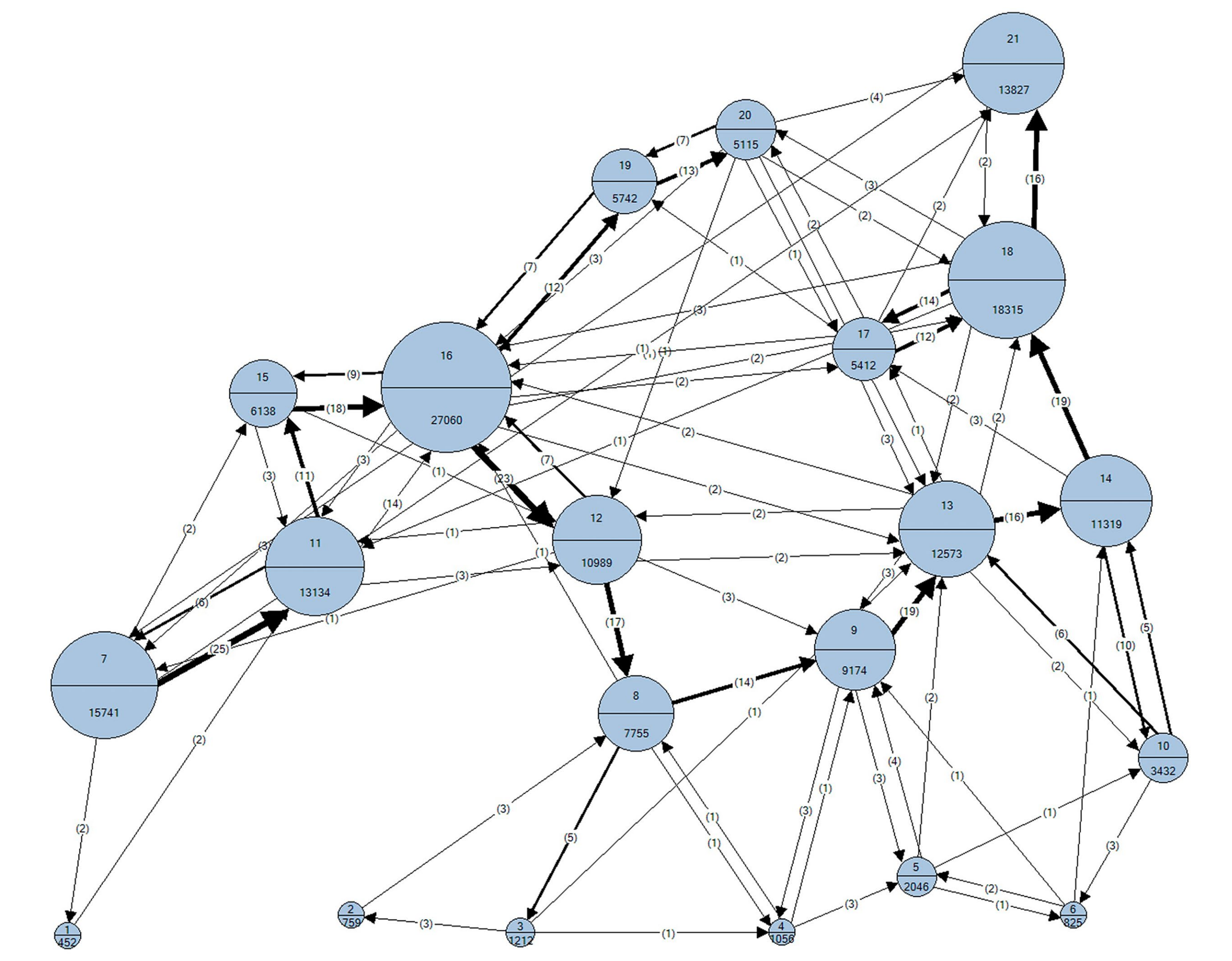


FIGURE 3
Gaze sequence of climbers during route previewing.

Effects of pre-planning on motor execution

Regarding the impact of pre-planning during route previewing on motor execution when completing the route, comparisons between the holds used during execution that were looked at before vs. not looked at before showed that significantly more holds were looked at than not looked at ($X^2 = 121.15$, $p < 0.001$, $\varphi = 0.86$, $d = 3.36$). From this result, it can be inferred that during execution, the climbers relied on the holds they had visually scanned in their pre-planning during the route preview. Further, analyzing the holds looked at during pre-planning revealed that significantly more holds were later used than not used during route execution ($X^2 = 22.44$, $p < 0.001$, $\varphi = 0.09$, $d = 0.36$) (see Table 1). This result suggests that looking at holds during pre-planning informs the subsequent use during route execution as further discussed below.

We further analyzed whether the *duration* of fixations also differed for holds used vs. not used during route execution. The dependent *t*-test ($t(17) = 5.10$, $p < 0.001$, $d = 1.20$) revealed that, indeed, holds used were looked at longer ($M = 754.56$ ms; $SD = 244.58$; $SE = 57.64$) than holds that were not used during route execution ($M = 396.80$ ms; $SD = 165.79$; $SE = 39.07$). Together, the findings on the impact of route previewing on execution suggest that the visual search during pre-planning actually informs the motor performance during route execution as indicated in the Supplementary material (please see Video File S1).

Relation between pre-planning and motor execution

Regarding the relation between pre-planning and motor execution of the routes execution, overall *VP* was significantly correlated with *MP* ($rho = 0.796$, $p = 0.001$). In addition, *Tclimb* and *Ntrial* were positively correlated ($rho = 0.661$, $p = 0.003$), which indicates that climbing performance was reliably measured in the experimental task.

Table 2 showed that *VP* and *MP* were negatively related to *Tclimb* and *Ntrial* in the climbing task. Correlational analyses also indicated that for three of the "key" holds (hand-holds 8, 14, and 18), the *VP* and *MP* of climbers were positively related to the fixation time, while the respective correlation was negative for the deceptive hand-hold 17.

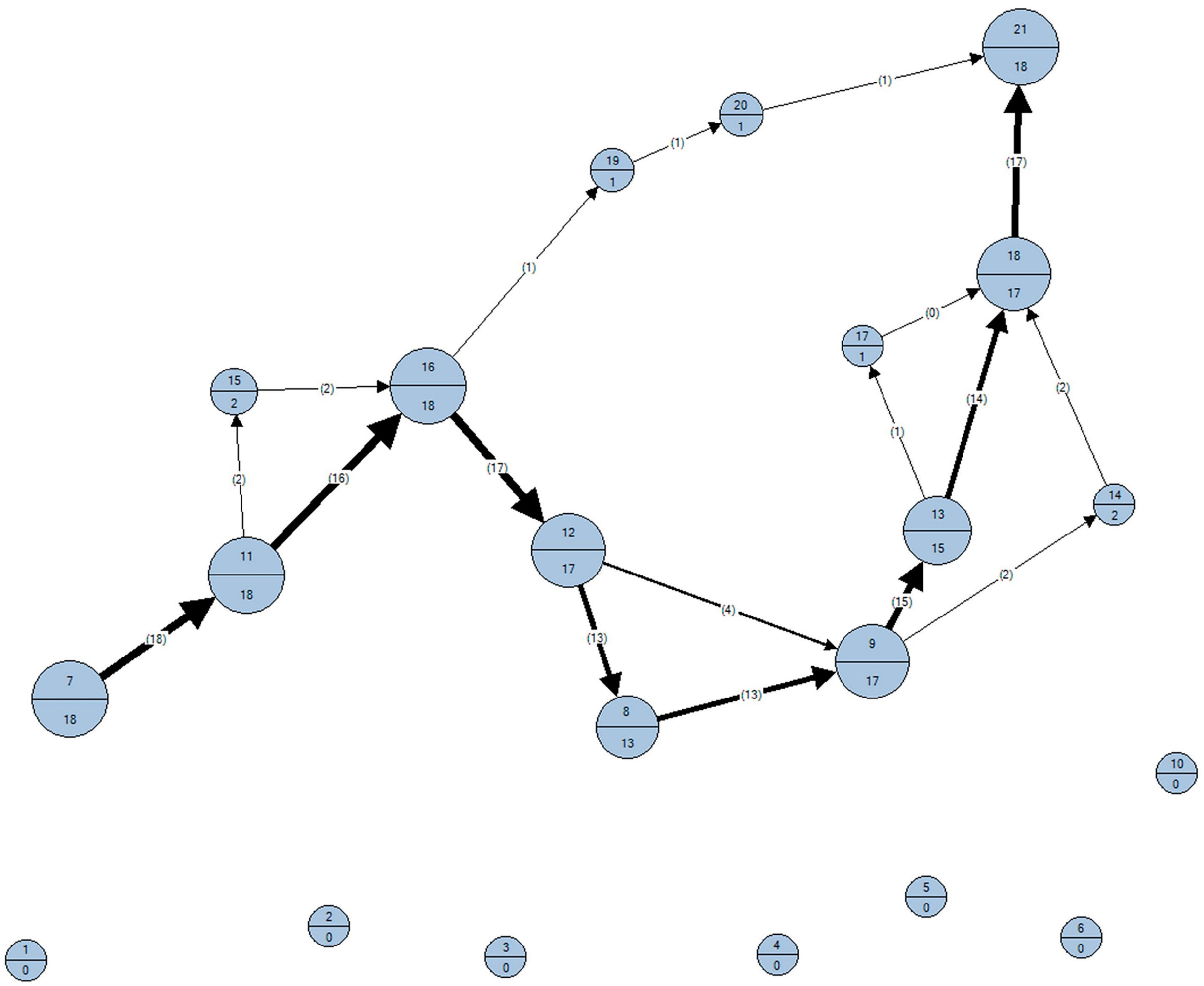


FIGURE 4
Grasping sequence of climbers during route execution.

TABLE 1 Frequency distribution and percentage of holds looked at and not looked at during route pre-planning that were later used and not used during route execution.

		Gaze		
		Yes	No	Total
Used	Yes	159 (42.1%)	5 (1.3%)	164
	No	85 (22.5%)	129 (34.1%)	214
		244	134	378

This indicates that looking longer at some "key" holds was associated with better visual and motor performance, while looking longer at the deceptive hold was associated with worse visual and motor performance.

The role of experience in pre-planning and motor execution

Regarding the role of experience in pre-planning the route during previewing and motor execution of the route, correlational analyses revealed that the number of years of climbing training was positively correlated to *VP* ($rho = 0.560$; $p = 0.016$) and *MP* ($rho = 0.537$; $p = 0.021$), and, as expected, negatively correlated to T*climb* ($rho = -0.533$; $p = 0.023$). There were no significant correlations of experience with the gaze strategies for holds looked at and used ($rho = 0.414$, $p = 0.098$), although experienced climbers with more years of training looked at holds not used for a significantly shorter amount of time ($rho = -0.614$, $p = 0.009$).

None of the models (linear, quadratic, growth function) yielded a significant fit for the duration of fixations for holds looked at and used. For the holds looked at but not used, the linear ($F(1, 15) = 11.42$, $p = 0.004$, $b1 = -29.94$, $R^2 = 0.43$), quadratic ($F(2, 14) = 5.35$, $p = 0.019$, $b1 = -34.09$, $b2 = 0.44$, $R^2 = 0.43$), and growth model ($F(1, 15) = 16.22$, $p = 0.001$, $b1 = -0.082$, $R^2 = 0.52$) were significant. The growth model with years of training explained 52% of variance.

Discussion

Our study tested, in experienced climbers, how to pre-plan a climbing strategy during route previewing and how climbers actually perform the route during route execution. Our findings support the

TABLE 2 Significant relations (rho) between study variables.

	Visual performance	Motor performance
Climbing time	−0.892**	−0.887**
Number of trials	−0.546*	−0.572*
Fixation time on hold8	0.474*	0.740**
Fixation time on hold14	472*	0.595**
Fixation time on hold17	−0.634**	−0.719**
Fixation time on hold18	0.535*	0.578*

*$p < 0.05$; **$p < 0.01$.

general notion of embodied planning that pre-planning and execution are intertwined (Musculus et al., 2021). This tight link between visual and motor performance in climbers is indicated by the correlations of hand-holds fixated at during pre-planning in the route preview and used during route execution. Further supporting the visual-motor link, visual performance was positively connected to motor performance. This can also be seen as an indicator of a reliable measure of expertise. Additionally, a positive correlation was found between the climbers' visual performance and the duration of fixations on three prominent "key" holds pre-selected by the experts, and negative correlation with one deceptive hand-hold. Together, the findings of the present study demonstrate that the visual search during pre-planning actually informs motor performance during route execution. This suggests the dynamic interaction of visual and motor processes as suggested by embodied planning in climbing (Musculus et al., 2021).

Regarding the interpretation of results, we initially reasoned that the three "key" hand-holds of the climbing wall (holds 8, 14, and 18; see Figure 1) were positively associated with the visual and motor performance of the climbers because they constitute specific crux points (e.g., the most difficult parts of the route) constraining the perception of their action opportunities at the climbing wall (Seifert et al., 2017). This might favor a visual strategy that has previously been referred to as a "sequence of blocks," consisting of scanning a route by chunking 2–4 hand-holds into a block. This strategy enables climbers to visualize alternative solutions while preparing for the route (Grushko and Leonov, 2014). According to Grushko and Leonov, this visual strategy is the most common visual pattern of climbers because it is connected to the tactical component of training. However, the climbers seemed to perform not only the "sequence of blocks" strategy but also an "ascending strategy" indicated by longer fixations at hand-holds 7, 11, 16, and 21 compared to other ones (see Figure 1). The "ascending strategy" is characterized by directing the gaze starting from below and then straight upwards, finishing the preview on the highest hold. Through this strategy, participants seem to inspect the most important ("key") holds of the wall and their respective features (e.g., shape, orientation, size) in order to infer how reach, graps, or use them during route execution (Grushko and Leonov, 2014; Seifert et al., 2017).

More specifically, we firstly suggest that the time of route previewing provided climbers an opportunity to enrich their planning of perceptions (i.e., perceived events) and actions (i.e., to-be-produced events), leading to a decreased performance time in the climbing sequence. We reasoned that climbers exploited longer fixations on some "key" holds during the initial viewing of the route, based on their motor repertoire accumulated in climbing environments (i.e., action possibilities for long-term planning; see Rietveld and Kiverstein, 2014). Therefore, past climbing experiences could guide the gaze of climbers toward the relevant holds of the climbing wall during route previewing, even when they were not moving (i.e., an offline action specific effect on perception; Schütz-Bosbach and Prinz, 2007). This effect is relevant for an understanding of what is simulated during the pre-planning phase and adds to previous work that focused on climbing (e.g., Pezzulo et al., 2010; Bläsing et al., 2014).

Second, we argue that the holds more fixated on during route previewing were used during the execution of the route because the perception of these holds helped climbers to identify specific targets during "route reading" and to plan the forthcoming actions required to climb it, also before climbing the route (Seifert et al., 2017). From this view, the initial observation of climbing holds would evoke the corresponding reaching and/or grasping actions needed to effectively ascend the route (Vainio et al., 2008). Therefore, the initial observation of a climbing wall would activate a motor simulation of specific climbing movements, providing climbers with a prior estimate of their action possibilities to climb the wall (Pezzulo et al., 2010). Importantly, the present climbing study is – to the best of our knowledge – the first to use analyses establishing the direct relation between gaze (holds looked at; see Figure 3) and motor execution (holds used; see Figure 4). By analyzing the conditional frequencies and mean fixation times, this study demonstrates the functional connection of gaze behavior and motor execution.

Third, embodied planning strategies in climbing, such as how often and how long holds were looked at and used during route execution, were related to experience (years of training). Results revealed that, with more experience, climbers looked at holds not used for significantly shorter times and climbed faster. Indeed, a significant correlation was found between experience and fixation times on holds not used. Thus, the years of training were positively correlated to their visual and motor performance when climbing the wall. With these data, we argue that a refinement between visual information and movement patterns emerged in the experienced climbers of this study as a consequence of repeated expositions to specific routes and actions performed in climbing environments. It seems that more experienced climbers, in contrast to less experienced climbers, have learned which stimuli (here, hand-holds) are more informative than others for their overall goal of successfully ascending the climbing wall. This finding can be interpreted in the light of the "education of attention," a frequently reported learning process resulting in the specification of informational stimuli and information pick-up (van der Kamp and Renshaw, 2015). As a result, these specific experiences would lead to the benefit of a better interpretation of the climbing-route information available prior to climbing the wall because they enable the experienced climbers to focus more on the respective function of the information (Boschker et al., 2002). Previously, Hacques et al. (2021) found that both exploratory hand movements and visual activity of intermediate climbers were used to gather information about different climbing routes. Specifically, these climbers displayed fewer fixations, decreased the number of fixated areas of interest, and performed less exploratory hand movements following a learning period on a climbing wall. The authors reasoned that these findings could reveal a reorganization of climbers' gaze behavior with learning in a more structured order to better guide their forthcoming climbing actions.

Altogether, the visual behavior of climbers with more experience in this study seems to be more economical and focused on some hand-holds that are more informative than others (i.e., related to the overall goal of successfully ascending the climbing wall), compared to the visual patterns of climbers with less experience. Therefore, the expertise of climbers, gained after years of practice and training in indoor climbing, drove their gazes effectively to the relevant stimuli available in this specific environment. Additionally, expert rock climbers show not only a better cognitive processing of perceptual information but also a better visual "hardware" as indicated by a psychophysical optical tests (Marcen-Cinca et al., 2022).

These expertise differences between athletes of different skill levels regarding fixation location and fixation duration have been previously tested within the expert/non-expert paradigm (Mann et al., 2007; Gegenfurtner et al., 2011). For example, Gegenfurtner et al. (2011) found that expert athletes displayed shorter fixation durations, fixating more frequently at task-relevant areas and less on task-redundant areas, compared with non-experts. Similarly, Mann et al. (2007) concluded that expert performers´ eye movements were characterized by fewer fixations of longer duration than less skilled experts. Within the sport of climbing, a discriminating variable of the skill level of climbers has been the visual information they focus on. For example, Seifert et al. (2017) claimed that expert climbers used the time of route previewing more efficiently to link the visual information about reachable and graspable holds of a climbing wall with accurate climbing movements. These differences in visual search strategies have been also found in climbing coaches of different skill levels because experts fixated mostly at relevant aspects of a climber's movement, using fewer fixations of greater duration, compared to the novice climbers (Mitchell et al., 2020). Recently, Medernach et al. (2024) argued that skilled climbers in indoor climbing had superior memory abilities to remember more climbing holds and movements driven by better mental visualization and enhanced visual attention to functional aspects of boulders.

Before concluding, we would like to acknowledge the potential limitations of this study. First, our sample size was not very large but is close to the average of 20.6 participants that we found from reviewing 60 studies on natural visual search behavior in sports (Kredel et al., 2017). In addition, other past climbing studies with gaze measures used the same number of climbers as our study ($N = 18$ in Seifert et al., 2017) or even fewer ($N = 12$ in Nieuwenhuys et al., 2008). Therefore, it would be interesting in future studies to test whether the significant differences found with this small sample of climbers would remain for a higher number of participants. In line with this, the use of larger samples of climbers with major homogeneity regarding their climbing experiences in future climbing research designs, both in years and frequency of training per week, would ensure the testing of more reliable correlations between (visual and motor) climbing performance, holds looked at/not looked at, and holds used/not used.

Second, it can be argued that bodily information may be an important factor for climbers to succeed in pre-planning a route. Our measures did not allow us to quantify the body movement during the pre-planning phase, and we did not specifically instruct participants to use or not use their bodies, so we believe participants engaged their routine behavior. In future studies that go beyond our current investigations of gaze strategies during the pre-planning phase, it maybe worthwhile to quantify bodily composition, capability, and movements of climbers, relating them to the climbing performance.

Third, we used different numbers of deceptive and target holds in our setting that may reflect the realistic and valid situation that multiple ways in planning a route are potentially good, resulting in more target holds and fewer deceptive holds. However, it could be argued that using 10 target holds and four deceptive holds might produce an effect that a climber who uses all target holds to reach the goal will potentially look at more target holds compared to deceptive holds. This effect could be systematically investigated in future studies using different relations of target and deceptive holds.

Conclusion

The present study shows that the pre-planning processes captured through visual search behavior inform the motor execution when climbing a route. In addition, this study is the first to provide empirical evidence on the proposed link between perceptual-cognitive processes of an initial planning phase and motor processes when executing the plan (i.e., embodied planning in climbing; see Musculus et al., 2021). The findings presented here reinforce the contribution of previous specific motor experiences on action perception (Beilock, 2008), known as the "motor experience hypothesis" (Cañal-Bruland et al., 2010) and often discussed in the context of embodiment in sports (Raab, 2017). Specifically, the accumulation of climbing experiences enhanced climbers´ action-perception coupling, enabling them to find hand-holds for better route completion.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Bioethics and Biosecurity Committee of University of Extremadura (Spain) on 6 March 2018 (nº 33/2018). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

VL-dC: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft. JM: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. LM: Formal analysis, Methodology, Writing – review & editing. MR: Methodology, Supervision, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. The project was partly funded by the German Research Foundation within the priority programme "The Active Self" granted to Markus Raab (RA 940/21-1).

Acknowledgments

The authors acknowledge all climbers who voluntary participated in this study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2024.1337878/full#supplementary-material

References

Beilock, S. L. (2008). Beyond the play field: sport psychology meets embodied cognition. *Int. Rev. Sport Exerc. Psychol.* 1, 19–30. doi: 10.1080/17509840701836875

Bläsing, B. E., Güldenpenning, I., Koester, D., and Schack, T. (2014). Expertise affects representation structure and categorical activation of grasp postures in climbing. *Front. Psychol.* 5:1008. doi: 10.3389/fpsyg.2014.01008

Boschker, M. S. J., Bakker, F. C., and Michaels, C. F. (2002). Memory for the functional characteristics of climbing walls: perceiving affordances. *J. Motor Behav.* 34, 25–36. doi: 10.1080/00222890209601928

Cañal-Bruland, R., van der Kamp, J., and van Kesteren, J. (2010). An examination of motor and perceptual contributions to recognizing deception in others' actions. *Hum. Mov.Sci.* 29, 94–102. doi: 10.1016/j.humov.2009.10.001

Draper, N., Dickson, T., Blackwell, G., Fryer, S., Priestley, S., Winter, D., et al. (2011). Self-reported ability assessment in rock climbing. *J. Sports Sci.* 29, 851–858. doi: 10.1080/02640414.2011.565362

Draper, N., Giles, D., Schöffl, V., Konstantin Fuss, F., Watts, P., Wolf, P., et al. (2015). Comparative grading scales, statistical analyses, climber descriptors and ability grouping: international rock climbing research association position statement. *Sports Technol.* 8, 88–94. doi: 10.1080/19346182.2015.1107081

Faul, F., Erdfelder, E., Lang, A. G., and Buchner, A. (2007). G*power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* 39, 175–191. doi: 10.3758/bf03193146

Gegenfurtner, A., Lehtinen, E., and Säljö, R. (2011). Expertise differences in the comprehension of visualizations: a meta-analysis of eye-tracking research in professional domains. *Educ. Psychol. Rev.* 23, 523–552. doi: 10.1007/s10648-011-9174-7

Grushko, A. I., and Leonov, S. V. (2014). The usage of eye-tracking technologies in rock-climbing. *Proc. Soc. Behav.* 146, 169–174. doi: 10.1016/j.sbspro.2014.08.075

Hacques, G., Komar, J., and Seifert, L. (2021). Learning and transfer of perceptual-motor skill: relationship with gaze and behavioral exploration. *Atten. Percept. Psychol.* 83, 2303–2319. doi: 10.3758/s13414-021-02288-z

IFSC (2023). Disciplines. Available at: https://www.ifsc-climbing.org/index.php/world-competition/disciplines

IFSC (2022). 2022 Rules. Available at: https://cdn.ifsc-climbing.org/images/Website/2022_IFSC_Rules_201.pdf

Kredel, R., Vater, C., Klostermann, A., and Hossner, E. J. (2017). Eye-tracking technology and the dynamics of natural gaze behavior in sports: a systematic review of 40 years of research. *Front. Psychol.* 8:1845. doi: 10.3389/fpsyg.2017.01845

Künzell, S., Giles, D., España-Romero, V., Legreneur, P., and Balas, J., (Eds.) (2021). *Research in sport climbing*. Lausanne: Frontiers Media SA.

Mann, D. T. Y., Williams, A. M., Ward, P., and Janelle, C. M. (2007). Perceptual-cognitive expertise in sport: a meta-analysis. *J. Sport Exerc. Psychol.* 29, 457–478. doi: 10.1123/jsep.29.4.457

Marcen-Cinca, N., Sanchez, X., Otin, S., Cimarras-Otal, C., and Bataller-Cervero, A. V. (2022). Visual perception in expert athletes: the case of rock climbers. *Front. Psychol.* 13:903518. doi: 10.3389/fpsyg.2022.903518

Medernach, J. P., Henz, J., and Memmert, D. (2024). Mechanisms underlying superior memory of skilled climbers in indoor bouldering. *J Sport Sci.* doi: 10.1080/02640414.2023.2300569, [Online ahead of print]

Mitchell, J., Maratos, F. A., Giles, D., Taylor, N., Butterworth, A., and Sheffield, D. (2020). The visual search strategies underpinning effective observational analysis in the coaching of climbing movement. *Front. Psychol.* 11:1025. doi: 10.3389/fpsyg.2020.01025

Morenas, J., Luis, V., Leyton, M., Gómez-Valadés, J. M., and Gómez, J. S. (2013). Description of the finger mechanical load of climbers of different levels during different hand grips in sport climbing. *J. Sports Sci.* 31, 1713–1721. doi: 10.1080/02640414.2013.797592

Morenas, J., Luis, V., and Manso, L. J. (2018). Design and development of a low-cost mask-type eye tracker to collect quality fixation measurements in the sport domain. *Proc. IMechE Part P J. Sports Eng. Technol.* 233, 116–125. doi: 10.1177/1754337118808177

Musculus, L., Ruggeri, A., and Raab, M. (2021). Movement matters! Understanding the developmental trajectory of embodied planning. *Front. Psychol.* 12:633100. doi: 10.3389/fpsyg.2021.633100

Nieuwenhuys, A., Pijpers, J. R., Oudejans, R. R., and Bakker, F. C. (2008). The influence of anxiety on visual attention in climbing. *J. Sport Exerc. Psychol.* 30, 171–185. doi: 10.1123/jsep.30.2.171

Paterson, G., van Der Kamp, J., Bressan, E., and Savelsbergh, G. (2013). The effects of perception-action coupling on perceptual decision-making in a self-paced far aiming task. *Int. J. Sport Psychol.* 44, 179–196. doi: 10.7352/IJSP2013.44.179

Pezzulo, G., Barca, L., Bocconi, A. L., and Borghi, A. M. (2010). When affordances climb into your mind: advantages of motor simulation in a memory task performed by novice and expert rock climbers. *Brain Cogn.* 73, 68–73. doi: 10.1016/j.bandc.2010.03.002

Raab, M. (2017). Motor heuristics and embodied choices: how to choose and act. *Curr. Opin. Psychol.* 16, 34–37. doi: 10.1016/j.copsyc.2017.02.029

Raab, M., and Araújo, D. (2019). Embodied cognition with and without mental representations: the case of embodied choices in sports. *Front. Psychol.* 10:1825. doi: 10.3389/fpsyg.2019.01825

Rietveld, E., and Kiverstein, J. (2014). A rich landscape of affordances. *Ecol. Psychol.* 26, 325–352. doi: 10.1080/10407413.2014.958035

Sanchez, X., Lambert, P., Jones, G., and Llewellyn, D. J. (2012). Efficacy of pre-ascent climbing route visual inspection in indoor sport climbing. *Scand. J. Med. Sci. Sport* 22, 67–72. doi: 10.1111/j.1600-0838.2010.01151.x

Sanchez, X., Torregrossa, M., Woodman, T., Jones, G., and Llewellyn, D. J. (2019). Identification of parameters that predict sport climbing performance. *Front. Psychol.* 10:1294. doi: 10.3389/fpsyg.2019.01294

Saul, D., Steinmetz, G., Lehmann, W., and Schilling, A. F. (2019). Determinants for success in climbing: a systematic review. *J. Exerc. Sci. Fit.* 17, 91–100. doi: 10.1016/j.jesf.2019.04.002

Schütz-Bosbach, S., and Prinz, W. (2007). Perceptual resonance: action-induced modulation of perception. *Trends Cogn. Sci.* 11, 349–355. doi: 10.1016/j.tics.2007.06.005

Seifert, L., Cordier, R., Orth, D., Courtine, Y., and Croft, J. L. (2017). Role of route previewing strategies on climbing fluency and exploratory movements. *PLoS One* 12:e0176306. doi: 10.1371/journal.pone.0176306

Seifert, L., Dicks, M., Wittmann, F., and Wolf, P. (2021a). The perception of nested affordances: an examination of expert climbers. *Psychol. Sport Exerc.* 52:101843. doi: 10.1016/j.psychsport.2020.101843

Seifert, L., Dicks, M., Wittmann, F., and Wolf, P. (2021b). The influence of skill and task complexity on perception of nested affordances. *Atten. Percept. Psychol.* 83, 3240–3249. doi: 10.3758/s13414-021-02355-5

Vainio, L., Symes, E., Ellis, R., Tucker, M., and Ottoboni, G. (2008). On the relations between action planning, object identification, and motor representations of observed actions and objects. *Cognition* 108, 444–465. doi: 10.1016/j.cognition.2008.03.007

van der Kamp, J., and Renshaw, I. (2015). "Information-movement coupling as a hallmark of sport expertise" in *Routledge handbook of sport expertise*. eds. J. Baker and D. Farrow (London: Routledge/Taylor & Francis Group), 50–63.

van Knobelsdorff, M. H., van Bergen, N. G., van der Kamp, J., Seifert, L., and Orth, D. (2020). Action capability constrains visuo-motor complexity during planning and performance in on-sight climbing. *Scand. J. Med. Sci. Spor.* 30, 2485–2497. doi: 10.1111/sms.13789

Williams, A. M., and Davids, K. (1998). Visual search and biological motion perception in tennis. *Res. Q. Exerc. Sport* 69, 111–128. doi: 10.1080/02701367.1998.10607677

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 26 February 2024
DOI 10.3389/fpsyg.2024.1328991

OPEN ACCESS

EDITED BY
Kylie Ann Steel,
Western Sydney University, Australia

REVIEWED BY
Ayoub Asadi,
Iowa State University, United States
David Sherwood,
University of Colorado Boulder, United States

*CORRESPONDENCE
Sean Müller
✉ sean.muller@federation.edu.au

RECEIVED 27 October 2023
ACCEPTED 08 February 2024
PUBLISHED 26 February 2024

CITATION
Müller S, Beseler B, Morris-Binelli K and Mesagno C (2024) Temporal samples of visual information guides skilled interception. *Front. Psychol.* 15:1328991.
doi: 10.3389/fpsyg.2024.1328991

Temporal samples of visual information guides skilled interception

Sean Müller[1]*, Bradley Beseler[2], Khaya Morris-Binelli[3] and Christopher Mesagno[4,5]

[1]Centre for Smart Analytics, Federation University Australia, Ballarat, VIC, Australia, [2]Institute of Education, Arts & Community, Federation University Australia, Ballarat, VIC, Australia, [3]School of Health Sciences, The University of Notre Dame Australia, Fremantle, WA, Australia, [4]Institute of Health and Sport, Victoria University, Melbourne, VIC, Australia, [5]Institute of Health and Wellbeing, Federation University Australia, Ballarat, VIC, Australia

This study investigated whether performance of an interceptive skill requires an intact visual-perception-action cycle. Eleven skilled male Australian rules football athletes (M_{age} = 17.54, SD = 0.15) were recruited from an elite developmental pathway squad for a within-subject study. Participants were required to kick a ball directly at a goal from a 20-meter distance while wearing a pair of stroboscopic glasses. The glasses were used to create four vision conditions. Condition one kept intact the visual-perception-action cycle with uninterrupted vision of the motor skill. Three other conditions included stroboscopic vision that presented temporal samples of vision, which interrupted the perception-action cycle through progressive increases to intermittent vision occlusion of the motor skill. Goal kick error of ball position relative to a central target line within the goal and number of successful goals kicked were measured. Written report of internal and external focus of attention was also measured after each vision condition. Generalized estimating equation analysis did not reveal a significant decrement in kick target error, nor accuracy of goals scored, across normal to stroboscopic vision conditions. Performance was maintained despite a shift in attention focus from external to internal across normal to stroboscopic vision conditions. These findings have theoretical and practical implications for the visual regulation of skilled interceptive actions.

KEYWORDS

visual-perception-action cycle, stroboscopic vision, interceptive skill, attentional focus, goal kicking

1 Introduction

The use of visual-perceptual information to guide action is crucial to a variety of motor skills including interception of a ball with a foot or by hand using an implement in sports (Hodges et al., 2021). Expertise and motor learning researchers are interested in understanding the mechanism that underpins visual-perception-action of these complex motor skills because they are executed in challenging contexts (Morris-Binelli and Müller, 2017). For example, a soccer penalty taker, attempting to score against the opposition goalkeeper, needs to use visual information to guide their run toward the ball and intercept it with spatiotemporal accuracy, as well as force, to launch it past the keeper into the goal to score (Tomeo et al., 2013). Knowing how the brain uses visual information to control such complex skills contributes to theoretical advancement, which will provide a strong foundation for future training and development of perceptual-cognitive-motor skills.

Visual control of action can be explained from three theoretical perception-action loops. First, open-loop control states that temporal samples of visual information in the environment guide ballistic type actions when there is no time for adjustments (Adams, 1971; Schmidt et al., 2019). Second, closed-loop control also states that temporal samples of visual information from the environment are used, but adjustments to ongoing action occur if the time constraints permit (Elliott et al., 2001, 2020). Third, continuous perception-action cycle based control states that visual-perception informs action, and on-going action further informs perception to achieve the skill goal (Magill and Anderson, 2021). It is unclear whether a seamless intact perception-action cycle that allows visual information to synchronize with on-going movement is crucial for successful completion of the skill goal. Expertise and motor learning researchers have manipulated visual information during complex *in-situ* sports skills to understand how spatiotemporal visual information is used for action.

The duration of visual information for action has been manipulated through the use vision occlusion glasses worn by the performer (Milgram, 1987). Elliott and colleagues (see Elliott and Bennett, 2020) have conducted research where intermittent visual information of a projected ball was presented during one handed catching. The main finding from these series of studies is that intermittent visual samples, rather than continuous vision, of ball flight information is sufficient to maintain catching performance. For complex whole body sports skills expertise, Abernethy et al. (2001) were the first to investigate whether temporal pick-up of visual information available prior to object flight (known as advance cues) could be used for action control. In simulated squash matches, vision of highly skilled and lesser skilled performers was occluded prior to the opponent's racquet-ball contact. Results revealed that highly skilled players were superior to lesser skilled players at moving into court position when preparing to intercept the ball. Accordingly, Abernethy et al. (2001) provided evidence that advance visual information could be used in open-loop fashion to control complex whole-body positioning in sport. Subsequent studies that used occlusion glasses, or props to occlude pre-object flight cues, have confirmed the contribution of advance visual information, aligning with open-loop control, for positioning the body for interception in tennis return of serve (Farrow and Abernethy, 2003), cricket batting (Müller et al., 2009), and ice hockey goal tending (Panchuk and Vickers, 2009). Further, through comparison of temporal visual occlusion during early sections of object flight to a no occlusion control condition that presented all object flight, highly skilled cricket batsmen and ice hockey goaltenders could make fine adjustments to their bat or stick to intercept a ball or puck, respectively (Müller and Abernethy, 2006; Müller et al., 2009; Panchuk and Vickers, 2009). This indicates that experts can make fine adjustments based on later occurring components of complex whole-body skills, which aligns with closed-loop and perception-action cycling accounts of action control.

More recently, stroboscopic glasses that present a fixed duration of vision for 100 milliseconds, within cyclical periods of visual occlusion that vary in duration, have been used to investigate visual control of action. Fransen et al. (2017) investigated junior soccer players dribbling efficiency across a course under normal and stroboscopic vision conditions. Fransen et al. reported that faster dribblers had a greater decrement in time to course completion and ball control accuracy compared to slower dribblers when vision was increasingly restricted. Furthermore, Beavan et al. (2020) investigated whether amateur soccer players could complete a ball reception and pass test across normal and stroboscopic vision conditions. Stroboscopic vision caused a decrease in test completion time and accuracy. Both these studies indicate that for junior and amateur players, continuous visual information for action is necessary to maintain performance of dribbling or repetitive kicking sports skills. These findings could be because at such skill levels predictive capability of action is not sufficiently developed to guide and/or adjust performance. Accordingly, it is unclear whether cyclical interruptions to visual-perception-action will impede performance in skilled athletes who as mentioned earlier have superior predictive capability. In addition, it is unclear whether temporal samples of visual information can be used to guide action in closed sports skills. Therefore, further investigation of how visual-perception-action cycling influences complex skills in higher level sports players is needed.

Given that vision and proprioceptive information are used during motor skill performance, with the former the dominant sensory modality (Lee and Aronson, 1974; Elliott and Bennett, 2020), occlusion paradigms may alter in part (if not in whole) a performer's attentional focus. External focus refers to attention that can be directed by a performer, such as a batter, to advance cues from an opponent pitcher or bowler, and by a penalty taker to the intended goal location of a soccer ball (Wulf et al., 2001). Alternatively, internal focus refers to attention that can be directed by a performer to aspects of the movement pattern used to strike or kick a ball (Wulf et al., 2001). The constrained action hypothesis predicts that internal focus of attention will de-automatize skilled movement patterns and result in a decrement in skilled performance (Wulf et al., 2001). Accordingly, studies that have manipulated performer external and internal focus by experimenter instructions of what to focus attention on report that internal focus results in decreased performance in sports skills such as golf putting (Beilock et al., 2002; Klostermann et al., 2014; An and Wulf, 2024), volleyball passing (Singh and Wulf, 2020), slalom skiing (Wulf et al., 2001), and cricket ball striking (Bull et al., 2022). More recently, in line with meshed control theory, which predicts that conscious and automatic processes can work synchronously during motor skill performance (Christensen et al., 2016), skilled golfers can switch attention from external to internal focus prior to ball-putter contact without a performance decrement (Wang et al., 2021). Accordingly, some internal focus could draw attention toward task-related proprioceptive information, which as mentioned earlier, contributes in part to motor skill performance (Herrebrøden, 2022). Stroboscopic glasses present a method where through decreased occlusion cycling and therefore increased vision, attention may partly be drawn externally, or through increased occlusion cycling and decreased vision, attention could be drawn more internally. Such a methodology presents a more direct way for the experimenter to induce internal or external attention focus compared to direct instruction of where to focus attention, which may have inherent experimental bias and inconsistency of data collection. Previous studies that manipulated internal and external attentional focus across vision and no-vision conditions have reported that complete availability of vision did not along with attention focus influence performance (Abdollahipour et al., 2016; Saemi et al., 2017). This suggests that visual information and attentional focus instructions operate independently to guide performance. However, such strictly manipulated attentional focus and vision conditions do not take into account the dynamic nature of attentional shifts that may contribute to visual control of action in expert performance (Wang et al., 2021; Herrebrøden, 2022). Having a method that can consistently create a partial focus of attention could determine how such manipulations influence skilled performance in sport skills (Wang et al., 2021; Herrebrøden, 2022).

The present study used the *set shot* kick in Australian football as the exemplar perceptual-motor skill to explore how visual information regulates action and how attentional focus might influence performance. The set shot, a similar skill to an National Football League punt where the ball is guided by one hand to be intercepted with their foot and kicked toward goal, is a key goal scoring option where an offensive player catches the ball (known as a mark), and from a standing start, runs toward, and kicks at the goal over an opposition player standing where the ball was marked (Mesagno and Mullane-Grant, 2010; Blair et al., 2020). The objective is to kick the ball between the two center posts to score six points, with a single point resulting when the ball is kicked between either of the two outer scoring sections. A complete miss of all sections results in a score of zero. We created conditions where the performer (kicker) wore a pair of stroboscopic glasses, then executed set shots under normal uninterrupted vision, and increasing cyclical occlusion-to-vision conditions. Based upon the literature discussed above, three hypotheses were formulated. First, if temporal samples of visual information were sufficient to control action, kicking accuracy would not decrease across uninterrupted (normal) to stroboscopic vision conditions. Second, if continuous perception-action cycling was critical for visual control of action, kicking accuracy would decrease from uninterrupted (normal) to stroboscopic vision conditions. Third, a shift in written report of attention from external to internal focus would occur as vision occlusion increased and this would result in a decrease in kicking accuracy.

2 Materials and methods

2.1 Participants

Eleven skilled male footballers were recruited from an Australian rules football elite developmental pathway team. These participants formed a current group of emerging expert players in the region of their state, which is consistent with the sport expertise literature (Connor et al., 2018). The mean age of players was 17.54 years (SD = 0.15, age range: 17–18 years). Based upon our generalized estimating equation analysis (see data analysis section), an *a-priori* power analysis conducted in G*Power (Version 3.1.9.7) with $\alpha = 0.05$, 80% power, and 95% confidence interval, for a repeated measures analysis, indicated that 40 trials per participant (440 trials in total) could detect a small effect size. Participants volunteered for the study and provided written informed consent, with ethics approval obtained from the lead institution (permit number E21-004).

2.2 Materials and procedure

Participants wore Senaptec stroboscopic glasses (Model 26125) to create four vision conditions and completed set shot kicks at goal (see Mitroff et al., 2013 for details on glasses). Condition 1 (hereafter called normal vision) consisted of the glasses being worn, but were not activated, which provided clear vision of the run-up, kick action, and goal. Conditions 2, 3, and 4 consisted of the glasses being activated to Strobe settings 1 (67 ms), 5 (344 ms), and 8 (900 ms), occlusion time, respectively. The strobe feature involved the glasses cycling intermittently from a clear state that provided vision of the environment to an opaque state that occluded vision, with the clear state consistently 100 ms, and the opaque state set at 67 ms, 344 ms, and 900 ms for settings 1, 5, and 8, respectively (Mitroff et al., 2013). These pre-determined settings were selected by the experimenters to progressively increase cyclical intermittent vision occlusion time.

During the task, participants performed a set shot kick with an Australian football (oval shaped ball) at a vertical target ribbon located in the middle of a simulated Australian football goal (see Figure 1 for experimental set-up). Participants were instructed to kick at the ribbon using their normal set shot routine. The rationale for these instructions is that recent literature indicates that attentional focus is dynamic during the preparation to execution time course of motor skills, rather than being fixed as external or internal focus *per se* (Wang et al., 2021; Herrebrøden, 2022). Participants were permitted a 10-meter run-up and then kicked over an adult size mannequin that was positioned 20 meters from and directly in front of the goal in an indoor sports center. The mannequin simulated an opposition player standing in the position where the mark was taken. In a game, set shot kicks can be executed from directly in front of the goal face, so our task was representative of a typical Australian football game (Mesagno and Mullane-Grant, 2010; Blair et al., 2020). A Go-Pro camera (model HERO9 Black) sampling at 50 frames per second was positioned behind the mannequin to capture where the kicked ball entered the scoring area relative to the vertical target. Condition and trial number cue cards, as well as a calibration distance measure were filmed in the camera field of view. Footage was imported into Kinovea (version 0.8.15) software where a calibrated frame-by-frame analysis was conducted to calculate target error and to determine whether a goal or point was scored.

Prior to beginning the task, participants completed an Australian football specific physical warm-up and completed five set shot kicks without the stroboscopic glasses. Thereafter, participants completed 10 kicking trials in a block under each of the four vision conditions, which were counterbalanced across participants. The experimenter manually changed the settings on the glasses to correspond to the relevant vision condition prior to each new vision condition. After each kick, participants walked back to their starting position and were handed the ball by the experimenter for the next trial. At the completion of each vision condition block of trials, participants answered the following attention focus question by ticking a box in a booklet: "Where did you focus most on the last block of set shot kicks, on the target line or on my technique?." Self-report of attentional focus has been previously used in the literature (e.g., Wang et al., 2021). Participants were given 1–2 min break between vision condition blocks of trials to complete this question and for a small rest period.

2.3 Data analysis

The four primary dependent measures were mean absolute, constant, and variable error from the target as well as kick score. Absolute error from the target on the video record was determined by calculating the distance in centimeters from the middle of the ball to the

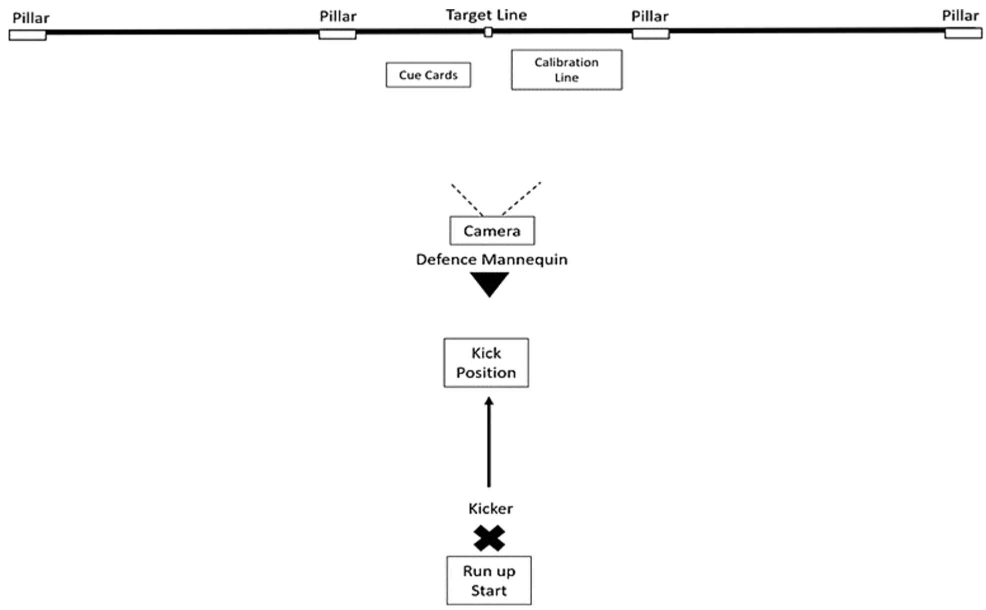


FIGURE 1
Schematic diagram (aerial view) of the experimental set-up for the study. The participant started in a stationary position (position ×), ran toward, and kicked the ball over a mannequin toward the vertical target line. The inside pillars represented the goal posts, and the outside pillars represented the point posts. The camera captured the ball position relative to the target line and whether a goal or point was scored. The calibration line was used to scale error measurements and cue cards were used to record condition/trial numbers.

closest point on the vertical target in the middle of the goal when the ball hit, or was alongside, the target (Magill and Anderson, 2021). Constant error was calculated as a signed deviation of absolute error with negative and positive values indicating kick error to the left and right of the ribbon, respectively (Magill and Anderson, 2021). Variable error was calculated as the standard deviation of constant error (Magill and Anderson, 2021). Kick score was determined by whether the ball traveled through the simulated goal or point scoring zones. The secondary dependent measure was external (i.e., on the target line) or internal (i.e., on technique) focus of attention. Five separate Generalized Estimating Equation (GEE) analyses were run to compare the dependent variables with vision condition as a fixed effect and individual participants included in the model as a repeated factor. As target error is a continuous measure, a linear GEE model was used and residuals were checked to be within ±3.29 for skewness and kurtosis (Ballinger, 2004; Field, 2013). For kicking accuracy and attention focus, which are dichotomous variables, binary logistic GEE models were used. These models do not require normality of residuals (Ballinger, 2004). GEEs were used as they allow for the correct modeling of repeated observations and can accommodate non-normally distributed data (Ghisletta and Spini, 2004). Alpha level was set at 0.05 and Holm-Bonferroni corrections were applied for follow-up post-hoc comparisons (Ballinger, 2004; Ghisletta and Spini, 2004).

3 Results

3.1 Target error

Figure 2 graphs the kick mean absolute error from the vertical target in the goal relative to normal and stroboscopic vision conditions. GEE found no significant difference in set shot kick mean absolute error across normal and stroboscopic vision conditions, χ^2 (3) = 3.45, $p = 0.328$. There was also no significant difference across stroboscopic vision conditions for mean constant error (Normal vision, $M = 32.31$ cm, SD = 170.16 cm; Strobe 1, $M = -0.73$ cm, SD = 193.01 cm; Strobe 5, $M = 46.78$ cm, SD = 194.28 cm; Strobe 8, $M = 32.19$ cm, SD = 223.87 cm), χ^2 (3) = 2.68, $p = 0.445$, and variable error (Normal vision, $M = 144.14$ cm, SD = 40.86 cm; Strobe 1, $M = 160.62$ cm, SD = 58.74 cm; Strobe 5, $M = 170.47$ cm, SD = 55.75 cm; Strobe 8, $M = 183.95$ cm, SD = 81.39 cm), χ^2 (3) = 4.76, $p = 0.190$.

3.2 Kicking accuracy

Figure 3 graphs the absolute percentage of goals and points scored relative to normal and stroboscopic vision conditions. GEE for kicking accuracy was significant, χ^2 (3) = 8.08, $p = 0.044$. However, post-hoc comparisons revealed no significant difference in the proportions of goals and points scored across normal to stroboscopic vision conditions ($p > 0.05$).

3.3 Attentional focus

Figure 4 graphs the absolute percentage of reported external and internal focus relative to normal and stroboscopic vision conditions. GEE for attention focus was significant, χ^2 (2) = 2930.72, $p < 0.001$. The source of the main effect was that Strobe 1 was significantly different to Strobe 8, $p = 0.015$. There was no significant difference in the proportions of attention focus between normal vision and Strobe 1, 5, and 8, as well as between Strobe 1 and 5, and Strobe 5 and 8, $p > 0.05$.

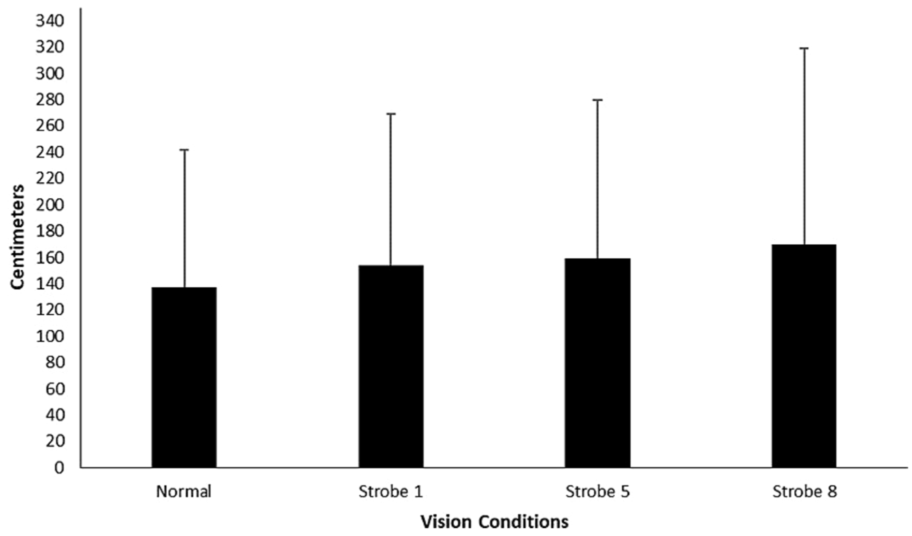


FIGURE 2
Absolute set shot kick error from the target (zero) in the goal under normal and stroboscopic vision conditions. Error bars represent standard deviations.

FIGURE 3
Absolute percentage of goals and points scored from the set shot kicks under the normal and stroboscopic vision conditions. Error bars are not plotted, as these are absolute values.

Although, differences in proportions of attention focus approached significance between normal vision and Strobe 8 conditions, $p = 0.061$.

4 Discussion

This study set out to investigate how skilled athletes use visual-perceptual information to guide action in a complex exemplar skill of the set shot kick in Australian football. Stroboscopic glasses worn by the performer allowed manipulation of vision from normal to intermittent occlusion cycling conditions that interrupted the continuous perception-action cycle. The findings contribute to the growing evidence of whether a continuous uninterrupted perception-action cycle is necessary for skilled performers to utilize visual information to guide action. In addition, the study provided evidence of athletes reporting shifts in their attentional focus when moving from normal vision to intermittent occlusion conditions, and how these shifts influenced their skill performance. Collectively, the findings contribute to furthering theoretical knowledge of visual regulation of action and associated attention focus of skilled perceptual-cognitive-motor skill.

Based upon open and closed-loop theory accounts of perceptual-motor control, the first hypothesis predicted that temporal samples of visual information would be sufficient to guide set shot kick performance. Alternatively, based upon perception-action cycling accounts of motor control, the second hypothesis predicted that

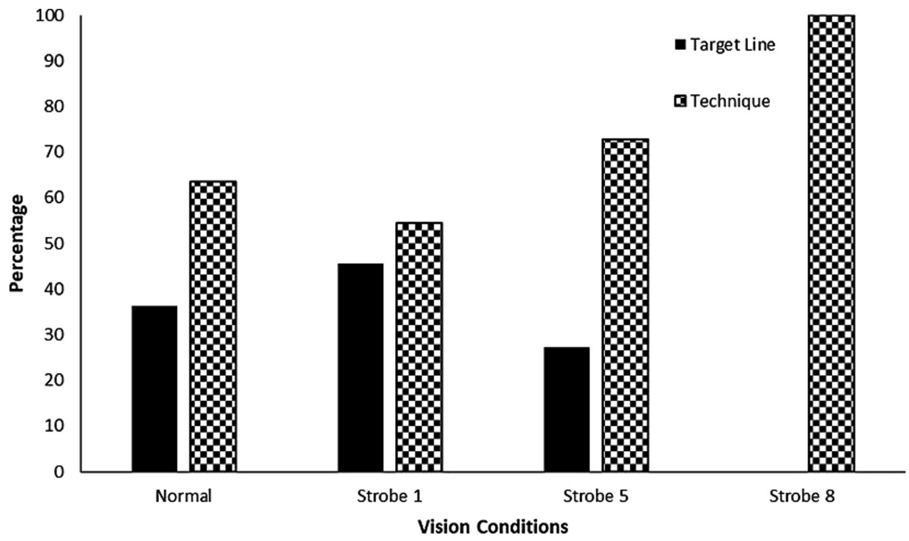


FIGURE 4
Absolute percentage of external and internal focus of attention under normal and stroboscopic vision conditions. Error bars are not plotted, as these are absolute values.

interruption of the vision-to-action cycle would decrease set shot kick performance. The first line of evidence revealed that kick target absolute, constant, and variable error (or local accuracy) did not change significantly across normal to stroboscopic vision conditions (see Figure 2). However, descriptively, variable error increased across normal vision to strobe 8 conditions suggesting that consistency of kick accuracy decreased as vision occlusion increased. A possible explanation is that increased vision occlusion may have resulted in minor delays of mapping temporal samples of visual information to limb positioning during the kicking action (Elliott and Bennett, 2020). Nonetheless, support for hypothesis one, but not two, was forthcoming. Skilled athletes in our study could use temporal samples of visual information to guide their run toward the mannequin to a kick position and guide the ball with their hand to be intercepted with their foot, to direct the ball over the mannequin at a target approximately 25 meters away from where it was kicked. This is consistent with the previously reported use of temporal samples of visual information to time positioning of the limb in one handed catching (Elliott and Bennett, 2020). Our study goes beyond that literature to demonstrate that temporal samples of visual information for action control is in line with previous expertise studies that have reported temporal pick-up of visual information for whole body positioning to intercept a ball in striking sports (Abernethy et al., 2001; Müller et al., 2009). Therefore, a continuous intact perception-action cycle does not seem necessary for local aiming (target error) at a target.

The second line of evidence supporting hypothesis one, and not hypothesis two, is that the proportion of goals and points scored did not change significantly across normal to interrupted vision conditions (see Figure 3). This indicates that temporal sampling of visual information to guide action did not impede the spatiotemporal interception of the ball by foot during the kick action for its resultant goal scoring opportunity. Again, this evidence is in line with temporal sampling of visual information to guide global performance in terms of the number of balls caught in the one handed catching literature (Elliott and Bennett, 2020). This evidence is also consistent with temporal sampling of object flight to intercept a ball accurately with a bat, or a puck with a glove or stick, respectively (Müller et al., 2009; Panchuk and Vickers, 2009). It is possible that temporal visual sampling may have been used to make fine adjustments to the kick run-up and/or ball-foot interception, as reported in striking sports (Müller et al., 2009; Panchuk and Vickers, 2009), but this requires investigation in follow-up studies. Our findings are not consistent with previous studies that reported decrements to performance in junior and amateur players (Fransen et al., 2017; Beavan et al., 2020). A possible reason is that at junior and lesser skilled levels, players may not have developed the capability to predict future events based upon temporal visual samples and require continuous visual feedback (Fransen et al., 2017). This also requires further investigation in future work where skill level is manipulated in the same task. Therefore, again, a continuous perception-action cycle was not necessary to maintain the global accuracy requirements of the motor skill in this study for skilled participants.

Broadly, internal focus of attention on a movement pattern has been associated with decreased performance compared to external focus upon environmental information or action effects (Wulf et al., 2001). Hypothesis three predicted that a change in self-reported attention focus from external to internal would result in a decrement to performance. As mentioned, there was no accompanying significant increase in local accuracy (target errors) or significant decrease in global accuracy (goals scored) across vision conditions (see Figures 2, 3), despite there being a significant change to predominantly internal focus of attention as vision occlusion increased from Strobe 1 to 8 (see Figure 4). There are two possible explanations for this. First, perhaps skilled athletes in our study had the intricate capability to switch attentional focus at a critical moment of skill phase (e.g., ball-foot impact) to maintain performance as has been reported in golf putting (Wang et al., 2021). Our questions probed allocation of attentional focus in a dichotomous perspective, which did not account for attentional switching. Second, participants' reported focus on technique may have been on proprioceptive control (Elliott and Bennett, 2020), rather than conscious focus or conscious control upon isolated components of the movement pattern in the kick. Given the intermittent nature of occlusion-to-vision cycling of the stroboscopic glasses, it is possible that temporal samples of visual information created a shared attention focus between external environmental and internal technique information despite written reports (Herrebrøden, 2022). Accordingly, intermittent sampling of visual information for action may be accompanied by dynamic attentional focus shifts, rather than previous conceptualization as static (or fixed) attentional focus during skill execution (Abdollahipour et al., 2016; Saemi et al., 2017). Collectively, these explanations warrant further research investigation, particularly since it is possible to shift attentional focus through manipulation of vision using stroboscopic glasses.

The theoretical implication of this study is that it contributes to furthering knowledge of visual regulation of complex interceptive action. The findings contribute to a growing body of evidence in open sports skills (Abernethy et al., 2001; Panchuk and Vickers, 2009; van Soest et al., 2010) that temporal samples of visual information also appear sufficient to maintain skilled performance in a closed sports skill. A reason why temporal samples of visual information are sufficient for action control is because a performer is faced with a multitude of sensorimotor information. That is, at any given time of complex open or closed sports skills, performers are faced with an array of visual, proprioceptive, and haptic information (Elliott and Bennett, 2020). The neuromotor system can only use a select amount of this sensorimotor information at particular instances in time to predict future environmental states and couple body action to complete the skill goal (Elliott and Bennett, 2020). Selection of sensorimotor information may also require dynamic shifts in attentional focus to maintain performance. Therefore, knowing that temporal samples are sufficient for action control presents opportunities for challenging practice and selective guidance of sensory information to accelerate perceptual-cognitive-motor skill.

Standard practice of interceptive sports skills is typically conducted under normal uninterrupted vision conditions. While this is representative of the sensory condition that motor skills are performed under in competition, there has been recent interest of whether visual occlusion paradigms can challenge visuomotor skill to accelerate performance. Initial intervention studies using stroboscopic vision training have reported improvements to skate and pass accuracy in ice-hockey (Mitroff et al., 2013), and that it might contribute to batting practice performance in baseball (Liu et al., 2020). The findings from our study suggest that stroboscopic glasses could be used as a screening tool for sports skills. For example, normal and stroboscopic vision conditions could be designed to determine whether athletes can use temporal visual samples to execute skills and how attentional focus is allocated during skill execution. This would provide information to guide design of visual-perceptual and/or proprioceptive-based attention focused training interventions to enhance skill performance (Mulligan and Hodges, 2014; Brenton et al., 2019).

5 Conclusion

The task designed for this study interrupted the perception-action cycle during a complex interceptive skill and found that temporal sampling of visual information, as well as combined internal and external focus of attention were sufficient to maintain performance. This indicates that a continuous intact perception-action cycling is not necessary for proficient perceptual-cognitive-motor skill. A potential limitation is that the number of kicks per vision condition was 10. However, our approach was to reduce any potential for athlete injury from increased number of kicks in a single session by ensuring that the statistical analysis was adequately powered. Future research could build upon our study in two main ways. First, written report of attentional focus under normal and stroboscopic vision could be expanded to probe whether external focus (i.e., proximal or distal, initial ball kick path or goal location, respectively), internal focus (technique or proprioceptive 'feel' of the movement) or combinations of both contribute to maintaining interceptive skill performance. This would contribute to concerns raised in the literature that all forms of internal focus may not be a limiting factor to performance (Herrebrøden, 2022). Second, an intervention study including normal and stroboscopic vision conditions is needed to determine whether complex open and closed motor skill performance can be accelerated. While initial attempts have been made to probe this question, stroboscopic training has been mixed with general visual skills training making it difficult to delineate causality (Liu et al., 2020). Both these future research directions will contribute to advancing the theoretical underpinning of visual control of action and how it can be enhanced.

Data availability statement

The datasets presented in this article are not readily available because athlete data cannot be shared. Requests to access the datasets should be directed to sean.muller@federation.edu.au.

Ethics statement

The studies involving humans were approved by Federation University Human Research Ethics Committee (approval number E21-004). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

SM: Conceptualization, Data curation, Formal analysis, Writing – original draft. BB: Conceptualization, Project administration, Writing – original draft, Data curation. KM-B: Conceptualization, Data curation, Formal analysis, Writing – original draft. CM: Conceptualization, Writing – original draft, Methodology.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

The authors would like to thank all participants and two student research assistants for their contributions to the research.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Abdollahipour, R., Psotta, R., and Land, W. M. (2016). The influence of attentional focus instructions and vision on jump height performance. *Res. Q. Exerc. Sport* 87, 408–413. doi: 10.1080/02701367.2016.1224295

Abernethy, B., Gill, D. P., Parks, S. L., and Packer, S. T. (2001). Expertise and the perception of kinematic and situational probability information. *Perception* 30, 233–252. doi: 10.1068/p2872

Adams, J. A. (1971). A closed-loop theory of motor learning. *J. Mot. Behav.* 3, 111–150. doi: 10.1080/00222895.1971.10734898

An, J., and Wulf, G. (2024). Golf skill learning: An external focus of attention enhances performance and motivation. *Psychol. Sport Exerc.* 70:102563. doi: 10.1016/j.psychsport.2023.102563

Ballinger, G. A. (2004). Using generalized estimating equations for longitudinal data analysis. *Organ. Res. Methods* 7, 127–150. doi: 10.1177/1094428104263672

Beavan, A., Hanke, L., Spielmann, J., Skorski, S., Mayer, J., Meyer, T., et al. (2020). The effect of stroboscopic vision on performance in a football specific assessment. *Sci. Med. Footb.* doi: 10.1080/24733938.2020.1862420

Beilock, S. L., Carr, T. H., MacMahon, C., and Starkes, J. L. (2002). When paying attention becomes counterproductive: impact of divided versus skill-focused attention on novice and experienced performance of sensorimotor skills. *J. Exp. Psychol. Appl.* 8, 6–16. doi: 10.1037/1076-898X.8.1.6

Blair, S., Robertson, S., Duthie, G., and Ball, K. (2020). Biomechanics of accurate and inaccurate goal-kicking in Australian football: group-based analysis. *PLoS One* 15:e0241969. doi: 10.1371/journal.pone.0241969

Brenton, J., Müller, S., and Harbaugh, A. G. (2019). Visual-perceptual training with motor practice of the observed movement pattern improves anticipation in emerging expert cricket batsmen. *J. Sports Sci.* 37, 2114–2121. doi: 10.1080/02640414.2019.1621510

Bull, H. G., Atack, A. C., North, J. S., and Murphy, C. P. (2022). The effect of attentional focus instructions on performance and technique in a complex open skill. *Eur. J. Sport Sci.* 23, 2049–2058. doi: 10.1080/17461391.2022.2150895

Christensen, W., Sutton, J., and McIlwain, D. J. F. (2016). Cognition in skilled action: Meshed control and the varieties of skill experience. *Mind Lang.* 31, 37–66. doi: 10.1111/mila.12094

Connor, J. D., Farrow, D., and Renshaw, I. (2018). Emergence of skilled behaviors in professional, amateur and junior cricket batsmen during a representative training scenario. *Front. Psychol.* 9:2012. doi: 10.3389/fpsyg.2018.02012

Elliott, D., and Bennett, S. J. (2020). Intermittent vision and goal-directed movement: a review. *J. Mot. Behav.* 53, 523–543. doi: 10.1080/00222895.2020.1793716

Elliott, D., Chua, R., and Helsen, W. F. (2001). A century later: Woodworth's (1899) two-component model of goal-directed aiming. *Psychol. Bull.* 127, 342–357. doi: 10.1037/0033-2909.127.3.342

Elliott, D., Lyons, J., Hayes, S. J., Burkitt, J. J., Hansen, S., Grierson, L. E. M., et al. (2020). The multiple process model of goal-directed aiming/reaching: insights on limb control from various special populations. *Exp. Brain Res.* 238, 2685–2699. doi: 10.1007/s00221-020-05952-2

Farrow, D., and Abernethy, B. (2003). Do expertise and the degree of perception-action coupling affect natural anticipatory performance? *Perception* 32, 1127–1139. doi: 10.1068/p3323

Field, A. (2013). *Discovering statistics using IBM SPSS statistics*. London, England: SAGE Publications.

Fransen, J., Lovell, T. W. J., Bennett, K. J. M., Deprez, D., Deconinck, F. J. A., Lenoir, M., et al. (2017). The influence of restricted visual feedback on dribbling performance in youth soccer players. *Mot. Control.* 21, 158–167. doi: 10.1123/mc.2015-0059

Ghisletta, P., and Spini, D. (2004). An introduction to generalized estimating equations and an application to assess selectivity effects in a longitudinal study on very old individuals. *J. Educ. Behav. Stat.* 29, 421–437. doi: 10.3102/10769986029004421

Herrebrøden, H. (2022). Motor performers need task-relevant information: proposing an alternative mechanism for the attentional focus effect. *J. Mot. Behav.* doi: 10.1080/00222895.2022.2122920

Hodges, N. J., Wyder-Hodge, P. A., Hetherington, S., Baker, J., Besler, Z., and Spering, M. (2021). Topical review: perceptual-cognitive skills, methods, and skill-based comparisons in interceptive sports. *Optom. Vis. Sci.* 98, 681–695. doi: 10.1097/opx.0000000000001727

Klostermann, A., Kredel, R., and Hossner, E. J. (2014). On the interaction of attentional focus and gaze: the quiet eye inhibits focus-related performance decrements. *J. Sport Exerc. Psychol.* 36, 392–400. doi: 10.1123/jsep.2013-0273

Lee, D. N., and Aronson, E. (1974). Visual proprioceptive control of standing in human infants. *Percept. Psychophys.* 15, 529–532. doi: 10.3758/BF03199297

Liu, S., Ferris, L. M., Hilbig, S., Asamoa, E., LaRue, J. L., Lyon, D., et al. (2020). Dynamic vision training transfers positively to batting practice performance among collegiate baseball batters. *Psychol. Sport Exerc.* 51:101759. doi: 10.1016/j.psychsport.2020.101759

Magill, R. A., and Anderson, D. (2021). *Motor learning and control: concepts and applications*. New York: McGraw Hill.

Mesagno, C., and Mullane-Grant, T. (2010). A comparison of different pre-performance routines as possible choking interventions. *J. Appl. Sport Psychol.* 22, 343–360. doi: 10.1080/10413200.2010.491780

Milgram, P. (1987). A spectacle-mounted liquid-crystal tachistoscope. *Behav. Res. Methods Instrum. Comput.* 19, 449–456. doi: 10.3758/BF03205613

Mitroff, S. R., Friesen, P., Bennett, D., Yoo, H., and Reichow, A. W. (2013). Enhancing ice hockey skills through stroboscopic visual training: a pilot study. *Athl. Train. Sports Health Care* 5, 261–264. doi: 10.3928/19425864-20131030-02

Morris-Binelli, K., and Müller, S. (2017). Advancements to the understanding of expert visual anticipation skill in striking sports. *Can. J. Behav. Sci.* 49, 262–268. doi: 10.1037/cbs0000079

Müller, S., and Abernethy, B. (2006). Batting with occluded vision: an in situ examination of the information pick-up and interceptive skills of high -and low-skilled cricket batsmen. *J. Sci. Med. Sport* 9, 446–458. doi: 10.1016/j.jsams.2006.03.029

Müller, S., Abernethy, B., Reece, J., Rose, M., Eid, M., McBean, R., et al. (2009). An in-situ examination of the timing of information pick-up for interception by cricket batsmen of different skill levels. *Psychol. Sport Exerc.* 10, 644–652. doi: 10.1016/j.psychsport.2009.04.002

Mulligan, D., and Hodges, N. J. (2014). Throwing in the dark: improved prediction of action outcomes following motor training without vision of the action. *Psychol. Res.* 78, 692–704. doi: 10.1007/s00426-013-0526-4

Panchuk, D., and Vickers, J. N. (2009). Using spatial occlusion to explore the control strategies used in rapid interceptive actions: predictive or prospective control? *J. Sports Sci.* 27, 1249–1260. doi: 10.1080/02640410903156449

Saemi, E., Abdoli, B., Farsi, A., and Sanjari, M. A. (2017). The interaction of external/internal and relevant/irrelevant attentional focus on skilled performance: the mediation role of visual information. *Med. Sport* 70, 419–429. doi: 10.23736/S0025-7826.16.02951-3

Schmidt, R. A., Lee, T. D., Winstein, C. J., Wulf, G., and Zelaznik, H. (2019). *Motor control and learning: a behavioural emphasis*. Champaign, IL: Human Kinetics.

Singh, H., and Wulf, G. (2020). The distance effect and level of expertise: is the optimal external focus different for low-skilled and high-skilled performers? *Hum. Mov. Sci.* 73:102663. doi: 10.1016/j.humov.2020.102663

Tomeo, E., Cesari, P., Aglioti, S. M., and Urgesi, C. (2013). Fooling the kickers but not the goalkeepers: behavioral and neurophysiological correlates of fake action detection in soccer. *Cereb. Cortex* 23, 2765–2778. doi: 10.1093/cercor/bhs279

van Soest, A. J. K., Casius, L. J. R., de Kok, W., Krijger, M., Meeder, M., and Beek, P. J. (2010). Are fast interceptive actions continuously guided by vision? Revisiting Bootsma and van Wieringen (1990). *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1040–1055. doi: 10.1037/a0016890

Wang, K. P., Frank, C., Tsai, Y. Y., Lin, K. H., Chen, T. T., Cheng, M. Y., et al. (2021). Superior performance in skilled golfers characterized by dynamic neuromotor processes related to attentional focus. *Front. Psychol.* 12:633228. doi: 10.3389/fpsyg.2021.633228

Wulf, G., McNevin, N., and Shea, C. H. (2001). The automaticity of complex motor skill learning as a function of attentional focus. *Quart. J. Exp. Psychol.* 54, 1143–1154. doi: 10.1080/02724980143000118

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 27 May 2024
DOI 10.3389/fpsyg.2024.1363495

OPEN ACCESS

EDITED BY
Kylie Ann Steel,
Western Sydney University, Australia

REVIEWED BY
Alberto Cordova,
University of Texas at San Antonio,
United States
Riki Lindsay,
Federation University Australia, Australia

*CORRESPONDENCE
Erik C. Chang
✉ auda@ncu.edu.tw

RECEIVED 30 December 2023
ACCEPTED 13 May 2024
PUBLISHED 27 May 2024

CITATION
Tien H-P and Chang EC (2024) Inequivalent and uncorrelated response priming in motor imagery and execution.
Front. Psychol. 15:1363495.
doi: 10.3389/fpsyg.2024.1363495

Inequivalent and uncorrelated response priming in motor imagery and execution

Hsin-Ping Tien[1,2] and Erik C. Chang[1]*

[1]Action and Cognition Laboratory, Institute of Cognitive Neuroscience, College of Health Sciences and Technology, National Central University, Taoyuan, Taiwan, [2]Taiwan International Graduate Program in Interdisciplinary Neuroscience, National Central University and Academia Sinica, Taipei, Taiwan

Introduction: Theoretical considerations on motor imagery and motor execution have long been dominated by the functional equivalence view. Previous empirical works comparing these two modes of actions, however, have largely relied on subjective judgments on the imagery process, which may be exposed to various biases. The current study aims to re-examine the commonality and distinguishable aspects of motor imagery and execution via a response repetition paradigm. This framework aims to offer an alternative approach devoid of self-reporting, opening the opportunity for less subjective evaluation of the disparities and correlations between motor imagery and motor execution.

Methods: Participants performed manual speeded-choice on prime-probe pairs in each trial under three conditions distinguished by the modes of response on the prime: mere observation (Perceptual), imagining response (Imagery), and actual responses (Execution). Responses to the following probe were all actual execution of button press. While Experiment 1 compared the basic repetition effects in the three prime conditions, Experiment 2 extended the prime duration to enhance the quality of MI and monitored electromyography (EMG) for excluding prime imagery with muscle activities to enhance specificity of the underlying mechanism.

Results: In Experiment 1, there was no significant repetition effect after mere observation. However, significant repetition effects were observed in both imagery and execution conditions, respectively, which were also significantly correlated. In Experiment 2, trials with excessive EMG activities were excluded before further statistical analysis. A consistent repetition effect pattern in both Imagery and Execution but not the Perception condition. Now the correlation between Imagery and Execution conditions were not significant.

Conclusion: Findings from the current study provide a novel application of a classical paradigm, aiming to minimize the subjectivity inherent in imagery assessments while examining the relationship between motor imagery and motor execution. By highlighting differences and the absence of correlation in repetition effects, the study challenges the functional equivalence hypothesis of imagery and execution. Motor representations of imagery and execution, when measured without subjective judgments, appear to be more distinguishable than traditionally thought. Future studies may examine the neural underpinnings of the response repetition paradigm to further elucidating the common and separable aspects of these two modes of action.

KEYWORDS

motor imagery, functional equivalence hypothesis, motor simulation theory, S-R binding, repetition and binding

1 Introduction

The concept of motor imagery (MI), which involves mentally simulating body movements without any physically overt motor output, has long been linked to motor execution (ME; Jeannerod, 1995; O'Shea and Moran, 2017). Johnson (1982) initially illustrated the interference effect between MI and ME when both were disrupted by alternative tracking tasks. Since then, numerous studies have consistently highlighted the parallel characteristics of MI and ME, both in behavioral performance and the corresponding brain regions.

Evidence supporting the equivalence of MI and ME is found in various behavioral tasks. For example, studies involving drawing and writing tasks have shown that participants exhibit comparable task durations when merely imagining or actually performing the task (Decety et al., 1989). Moreover, a linear relationship exists between mental and physical efforts and autonomic responses, such as heart rate and pulmonary ventilation, during imagined or actual locomotion tasks (Decety et al., 1991). Notably, MI training has proven effective in enhancing performance in sports (Morone et al., 2022; Lindsay et al., 2023), surgical skills (Sapien and Rogers, 2010; Goble et al., 2021), muscle strength (Sidaway and Trzaska, 2005; Paravlic et al., 2018), and even improving motor function in individuals with various movement deficits, such as those with cerebral palsy (Cabral-Sequeira et al., 2016; Gentile et al., 2024), post-stroke patients (Page et al., 2001; Monteiro et al., 2021), and Parkinson's disease patients (Tamir et al., 2007; Caligiore et al., 2017).

In addition to behavioral studies, neuroimaging research has identified overlapping brain regions for MI and ME, which include the primary motor cortex (M1; Munzert et al., 2009), premotor cortex (PMC; Gerardin et al., 2000; Hétu et al., 2013; Ridderinkhof and Brass, 2015), supplementary motor cortex (SMC; Lotze et al., 1999), cerebellum (Gerardin et al., 2000; Ridderinkhof and Brass, 2015), basal ganglia (Gerardin et al., 2000; Ridderinkhof and Brass, 2015), and posterior parietal cortex (PPC; Ridderinkhof and Brass, 2015). Electrophysiological data also reveal common motor-related sources in both MI and ME, characterized by event-related desynchronization (ERD) in the alpha band during cue-driven motor tasks (Pfurtscheller and Neuper, 1997; Brinkman et al., 2014; Duann and Chiou, 2016), as well as similar beta suppression in both modalities (Burianová et al., 2013). These findings support the notion of functional equivalence between ME and MI and provide insights into how MI can influence subsequent motor performance.

However, studying MI presents substantial challenges due to its covert nature, as it requires participants to construct mental scenarios without performing any observable actions. This often forces MI studies to depend on participants' self-reports in which they make conscious and subjective claims directly about the mental scenarios, leading to various complexities and potential inconsistencies in the research outcomes. One commonly used measure in MI research is the reported duration of MI (Guillot et al., 2012). Participants are instructed to mark the onset and offset of both imagined and actual actions, often by using a stopwatch in what is known as the mental chronometry approach (Posner, 2005). The time interval between these timestamps serves as the operational definition of performance duration, demonstrating reliability in accessing MI (Malouin et al., 2008). However, conclusions drawn from this "subjective" paradigm have yielded inconsistent results (Guillot et al., 2012). Some studies have reported equivalence between MI and ME in tasks involving gross motor control (arm movement: Gentili et al., 2004, walking: Papaxanthis et al., 2003) and fine motor control (drawing and writing: 4), Conversely, other studies have found the opposite pattern (Reed, 2002; Calmels et al., 2006; Louis et al., 2011). For example, biases in overestimating short durations and underestimating long durations (Wearden, 2003) have been found when estimating duration for MI compared to ME (Calmels et al., 2006). Additionally, durations of MI and ME for the same action are equivalent in aroused but not relaxed state (Louis et al., 2011).

The discrepancies observed can be partly attributed to biases in time perception. Studies have shown that when estimating durations for MI compared to ME, participants tend to overestimate shorter periods and underestimate longer ones (Wearden, 2003; Calmels et al., 2006). This indicates that differences in how MI and ME are processed over time may be significant. Furthermore, the necessity to switch tasks between reporting start and end times and engaging in imagery could delay the process, leading to the overestimation of brief durations. On the other hand, a lapse in attention during tasks that require longer durations might disrupt the imagery process, causing an underestimation in subjective time assessments.

The complexity in understanding the subjective duration of MI in research is further compounded by the demands of various tasks, which can create misleading perceptions influenced by previous experiences. This could potentially skew the perceived relationship between the subjective durations of MI and ME (Decety et al., 1989). Furthermore, explicit verbal knowledge of a motor skill has been shown to disrupt the smoothness of MI and increase its duration relative to ME (Reed, 2002).

In summary, the perceived duration of imagery in MI studies is subject to several influencing factors, including attentional dynamics such as task switching, attentional states, and the modulation of knowledge. These elements, although not directly related to motor control, can significantly impact interpretations of MI and its association with ME. It is crucial for researchers to meticulously acknowledge and mitigate these confounding variables in their investigations of MI to ensure more accurate and reliable conclusions.

The core aim of the present study is to introduce a less subjective method for evaluating the behavioral characteristics of MI through the application of the repetition effect. This effect, a well-documented phenomenon in motor control research, is known for creating short-term stimulus–response bindings across consecutive trials (Bertelson, 1965; Henson et al., 2014). Such binding, when formed in a given trial (n), results in quicker reaction times when overlapped stimulus and response features are encountered in the following trial (n + 1). Unlike the traditional reliance on measuring reported movement duration, the repetition effect provides a less subjective approach to assess the MI process by examining its influence on subsequent motor performance. This paradigm shifts toward using the repetition effect offers a novel way to reduce subjectivity while studying MI, focusing on measurable behavioral changes like reaction time, thereby circumventing the limitations of subjective self-reports.

The phenomenon of "action priming," characterized by the repetition effect, has been previously observed in MI (Li et al., 2005; Ramsey et al., 2010; Toovey et al., 2021). However, there have been concerns regarding the methodology employed in some of these studies. For instance, Toovey et al. (2021) reported repetition benefits in both MI and motor preparation, but these benefits may have been inflated due to the greater number of repeated prime-probe pairs in their experiment. Additionally, the presentation of prime and probe stimuli in either the left or right visual field introduced the influence of spatial congruency, potentially complicating the outcomes due to attentional orientation (Posner, 1980). In light of these concerns, the present study seeks to address these methodological issues in order to provide a more accurate and less subjective assessment of the behavioral characteristics of MI.

Besides the methodological issues, the inhibitory processes in motor imagery are distinct from the facilitation effects often seen in action priming studies. Studies, including those by Rieger et al. (2017), Bart et al. (2021), and Scheil and Liefooghe (2018), show that MI can lead to slower movement reaction times and both global and effector-specific inhibition, particularly when the same effector is involved in both imagined and executed actions. However, these inhibitory after-effects might be influenced by experimental instructions requiring participants to indicate imagined movement onset and offset, potentially leading to higher effector activity just before MI and introducing inhibitory effects.

Rieger et al. (2017) suggest that inhibition may be coded into the stimulus during MI, affecting action repetition. This effect could be influenced by the experimental setup, especially when visual cues intertwine MI and ME without prior preparation, as noted by Verbruggen et al. (2008). In such cases, the inhibitory process following the visual cue during MI could strengthen the stimulus-inhibition binding. In experiments where participants alternate between MI and ME, uncertainty about the response type can induce reactive inhibitory control, similar to the Go/No-Go paradigm (Rieger and Gauggel, 1999; Verbruggen et al., 2008). However, in practical MI applications, participants are typically well-prepared not to transmit motor commands during MI (Guillot et al., 2012), suggesting that the context and intention in MI significantly influence the nature of inhibitory processes.

The current study aims to verify the theoretical perspective from Jeannerod (1995), which posits similar causal roles and representations between MI and ME. To this end, we employ the "repetition effect paradigm," a less subjective behavioral approach, responding to previous inconsistencies noted in action priming research (Rieger et al., 2017; Toovey et al., 2021).

One key concern being addressed is the potential boosting of repetition benefits due to unbalanced ratios and attentional orientation. Additionally, the study aims to explore the possibility that repetition costs may be attributed to stronger suppression induced by the measurement process and reactive inhibition. The study takes measures to minimize the influence of attentional factors by avoiding spatial orienting in the central stimuli.

To investigate the nature of MI and its preparatory inhibition, the current study employs a block-design approach. In this design, repetition effects are probed using pairs of imagery-execution or execution-execution trials. By separating MI and ME trials into distinct blocks, participants are made aware in advance whether they should suppress their responses or not. This design helps reveal the pure influence of MI on subsequent execution.

Furthermore, the study employs a speeded-choice task that requires simple key presses in response to central primes and probes. This task is intentionally simpler than those used in previous MI studies, as it eliminates the need for coordination among multiple joints. The aim is to minimize uncontrollable covert attention switching between motor effectors and simplify the motor processing as much as possible.

Based on the functional equivalence hypothesis positing that MI and ME share similar representations and mechanisms, the current study expects the following outcomes:

i. *Significant repetition effects in both MI and ME:* This hypothesis is grounded in the idea that both imagined and executed motor actions engage similar neural and cognitive processes. As the repetition effect suggests that repeating a motor task can lead to faster and more efficient processing, observing significant repetition effects in both MI and ME conditions would support the notion that imagining an action and physically performing it involve overlapping cognitive and neural mechanisms. This hypothesis is consistent with theories that posit MI as a functional equivalent to ME in terms of motor planning and execution processes.
ii. *An equivalent magnitude of repetition effect in MI and ME*: This hypothesis extends the first by positing not only that repetition effects will be observed in both MI and ME but also that these effects will be of comparable magnitude. This is an important distinction, as it suggests a quantitative equivalence in how MI and ME influence motor processing. If the magnitude of repetition effects is similar across both conditions, it would provide stronger evidence for the functional equivalence hypothesis, indicating that MI and ME may exert similar levels of influence on motor system priming and readiness.
iii. *A significant correlation between the repetition effects observed in MI and ME*: The third hypothesis investigates the relationship between the repetition effects observed in MI and ME. A strong correlation would indicate that individuals who exhibit more pronounced repetition effects in ME are likely to show similar effects in MI, and vice versa. This correlation would provide evidence for individual differences in the capacity for motor simulation and execution, suggesting that the cognitive and neural mechanisms underlying MI and ME are not only similar but also interconnected. It would further imply that the ability to effectively engage in MI could be predictive of performance in ME, which could have significant implications for training and rehabilitation programs that utilize MI techniques.

Experiment 1 introduces the repetition priming paradigm to test the functional equivalence of MI and ME. Experiment 2 addresses potential confounders identified in Experiment 1, employing electromyography (EMG) to monitor and control for subthreshold muscle contractions during MI. Additionally, we extend the duration of prime responses to enhance the quality of the imagery process. These refinements aim to yield more reliable and insightful data on the MI-ME relationship.

2 Experiment 1: comparing repetition effects in MI and ME

In this experiment, we employed a forced-choice key-pressing task where the critical independent variables were the identification of prime and probe cues (i.e., repeated and non-repeated) and the type of prime response (i.e., passive observation, mental imagery of movement, or physical execution). The dependent variable of interest was the response time (RT) of the imperative probe response, which serves as an indicator of the after-effects of the prime response when comparing repeated and non-repeated conditions.

Previous research has established that the motor programming process during MI can contribute to the S-R binding (Ito, 1999; Liefooghe et al., 2021). Furthermore, if motor representations are constructed, the S-R binding should elicit facilitation, aligning with the findings of Bertelson (1965). In line with the theoretical framework proposed by Jeannerod (1995), we anticipate observing a repetition facilitation for MI that is equivalent to ME, as opposed to the absence of a facilitation effect associated with mere observation of the stimulus. Furthermore, we hypothesize a correlation between the repetition effects in MI and those observed in ME, suggesting a parallel in the way the brain processes these two modalities of motor planning.

2.1 Materials and methods

2.1.1 Participants

We recruited a total of 32 participants (8 males/24 females) whose ages ranging from 20 to 24 years (M = 21.34 years). Participants were from the student population of National Central University, Taiwan, and were screened to exclude known psychotic disorders or visual perception problems. All participants were strongly right-handed, as indicated by a mean score of 90.6 ± 12.5 on the Edinburgh Handedness Inventory - Short Form (Veale, 2014). The study protocol was approved by the Research Ethics Committee of National Taiwan University, and all participants provided informed consent after receiving a comprehensive explanation of their rights and the study procedures.

To determine the appropriate sample size for our study, we initially analyzed data from the first six participants who each completed a set of counterbalanced trials for every color-response pairing. Utilizing G*Power (Faul et al., 2007) we aimed for an effect size of Cohen's $d = 0.42$. This effect size was based on the observed difference between repeated and non-repeated trials specifically within the MI condition. The ideal power was set at 0.80, and the program estimated that 32 participants would be sufficient to reach an actual power of 0.80.

2.1.2 Task, stimuli, and apparatus

For response input, participants used a mechanical gaming keyboard (model MEKA G1, Thermaltake Esports, Taiwan) with a polling rate of 1,000 Hz. The task was displayed on a 23" LED flat panel monitor (AOC I2379VHE) with a vertical retrace rate of 60 Hz. The stimuli consisted of square boxes, each extending 1.5 degrees within the visual angle, presented against a gray background.

The primary task was a three-choice speeded response task, comprising two phases in each condition session (see Figure 1A). The color-response association phase followed a conventional speed-choice task format, including feedback. Subsequently, the main testing phase utilized a modified speed-choice task without feedback. Each trial in the main testing phase featured two target boxes, each of which could be one of three possible colors (i.e., red, blue, or green). These target boxes were separated by a transition box in white (see Figure 1B). Participants were given explicit instructions corresponding to different priming conditions (Perception, Imagery, or Execution) for responding to a first box (prime). Following their prime response, participants were then required to make a physical key response to a second box (probe). The specific key response for the box was imperatively determined by the color presented.

To ensure a reset between trial pairs and minimize the after-effect of the preceding trial pair, a transition box was inserted. Participants were required to physically press a key in response to the transition box using their left little finger, a finger not involved in the prime and probe responses. Throughout the task, participants were instructed to respond with both speed and accuracy.

2.1.3 Design

There were two independent variables: Prime Type (Execution/ Imagery/ Perception) and Repetition (Repeated/ Non-repeated), and both were within-subject. The dependent variable was the reaction time (RT) to the probe.

To reduce potential uncertainty in prime response and mitigate any reactive inhibition elicited by the Imagery cue, trials with the same prime condition were clustered together and conducted in distinct sessions. As a result, there were three separate sessions, each corresponding to one of the prime conditions: Perception, Imagery, and Execution.

In each session, a combination of 1:2 repeated and non-repeated trials was randomly intermixed to establish a balanced and unbiased distribution of predictability for the specific prime color. This randomization strategy was implemented to control for potential sequencing effects and uphold the integrity of the experimental design.

2.1.4 Procedure

Figure 1A provides an overview of the task flow in the current experiment. Participants completed three distinct sessions, each corresponding to one of the three prime conditions. To prevent automatic motor responses to prime stimuli based on prior experience, the Perception condition always assigned as the first session. The order of the Imagery and Execution conditions was counterbalanced across participants. According to insights from our pilot study, conducting Perception in all three sessions resulted in no systematic changes in the distinction between probe responses after observing the same stimulus vs. different ones across the sequence of sessions ($F(5, 55) = 0.39$, $MSE = 0.00$, $p = 0.85$). Had the Imagery or Execution condition been the initial session, there would have been a greater likelihood of participants' responses in the subsequent Perception condition being implicitly influenced by motor processes triggered from prior experience in responding to the prime boxes, even if they were instructed otherwise.

During the experiment, participants were seated comfortably in front of a laptop, maintaining a constant distance of 49 cm between their eyes and the screen using a chin-rest. They executed the task by positioning their right index, middle, and ring fingers, along with their left little finger, on the "←," "↓," "→," and "z" keys, respectively. Each session encompassed two distinct phases: the color-response association phase and the testing phase.

The color-response association phase aimed to establish the visuomotor association prior to the testing phase. In this phase, participants familiarized themselves with the relationship between colors and the corresponding fingers (e.g., "red"-"index finger," "blue"-"middle finger," and "green"-"ring finger"). Each trial in this phase

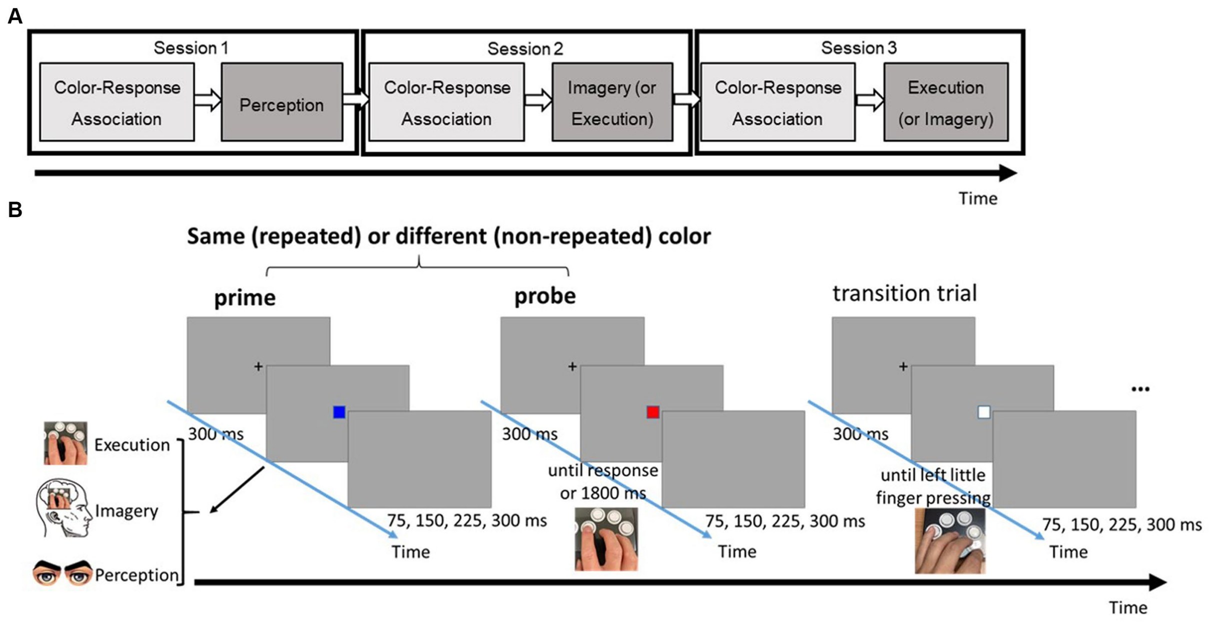


FIGURE 1
(A) The flow of three different task sessions. **(B)** Series of events in a typical trial of the three-choice, speeded response task in the testing phase. Note that there were three possible types of prime: perception, imagery, and execution; each requires a different type of response.

commenced with a fixation cross displayed at the center of the screen for 300 ms. Immediately following the fixation cross, a colored box was presented and disappeared upon the participant's response or after an 800 ms time limit. Visual feedback, such as "correct key," "wrong key," or "please press the key before the box disappears" was provided on the display following each response. The screen then remained blank for 1,000 ms as participants prepared for the next trial. After completing 12 consecutive trials, participants could take a break until they felt ready to proceed. If a participant achieved five consecutive correct responses for each color-finger pairing, the screen displayed the message "You have completed the color-response association phase," and the procedure advanced to the testing phase immediately.

In the testing phase, the repetition effect was assessed by calculating the difference in RT between repeated and non-repeated pairs. The testing phase consisted of two blocks, each containing six practice prime-probe pairs to familiarize participants with the procedure and 36 formal prime-probe pairs. One-third of the pairs featured repeated colored boxes, while two-thirds featured non-repeated ones. Participants were introduced to the trial-pair procedure at the beginning of the testing phase and completed six practice trial-pairs. The experimenter ensured participants had a clear understanding of the experiment after the practice. They had the freedom to commence the formal testing when they felt ready, with approximately 3 mins of rest between the end of the color-response association phase and the formal testing.

At the start of each testing pair, a fixation cross was presented for 300 ms, followed by the appearance of the first colored box. Required responses to the prime box varied based on the session: solely observing the box in the Perception condition, mentally simulating the corresponding keypress while experiencing the virtually recreated movement from a first-person perspective (kinesthetic imagery) in the Imagery condition, and physically pressing the key in the Execution condition. In the Execution condition, the prime box vanished immediately after the keypress or 1800 ms from its onset. In the other two priming conditions, where no actual response was made and, thus, the prime could not be erased at the RT, the duration of the prime presentation was individually adjusted based on the mean RT from the color-response association phase for each colored box. This adjustment was designed to minimize differences in the visible durations of primes across the three priming conditions.

Following the prime response, the screen remained blank for intervals of 75, 150, 225, or 300 ms before the appearance of a fixation cross that preceded the probe box. The probe box was either identical to its preceding prime box (repeated pair) or distinct from it (non-repeated pair). After the 300 ms fixation cross, the probe box was displayed on the screen, and participants were instructed to physically press the corresponding key in all conditions. The probe box disappeared immediately following the keypress or after 1800 ms if no response was registered. Following the presentation of the prime-probe pair, the screen went blank for 75, 150, 225, or 300 ms, followed by a 300 ms fixation cross. A white box then appeared at the center of the screen until participants pressed the key corresponding to their left little finger. Notably, no visual feedback was provided to indicate the accuracy after the key pressing during whole testing phase.

There were 36 trial-pairs in each testing block. After completing each block, participants provided feedback regarding their experience with the prime box on a 7-point Likert scale. In the Perception condition, participants reported their level of focus during the presentation of the prime box. In the Imagery condition, participants assessed the vividness of their motor imagery. In the Execution condition, participants indicated their confidence in making accurate responses. Following the entire experiment, participants also filled out the Chinese version of the Movement Imagery Questionnaire-Revision (cMIQ-R; Hall and Martin, 1997; Lin, 2011).

2.1.5 Data analysis

Probe trials with RTs that that deviated by more than three standard deviations from the mean of each condition for each participant were excluded. This exclusion was carried out using a recursive procedure (Van Selst and Jolicoeur, 1994). Additionally, probe RTs were excluded if the participant responded to the preceding prime in the Perception and Imagery conditions.

The remaining probe RTs were subjected to a two-way repeated-measures ANOVA with factors of Repetition (repeated and non-repeated) and Priming (Perception, Imagery, and Execution). To control for multiple comparisons, *p*-values from *post-hoc* pairwise comparisons were corrected using the step-down method with the Holm-Bonferroni adjustment (Holm, 1979).

To compare the repetition effect between the Imagery and Execution conditions, the differences in RT between non-repeated and repeated probes in these two conditions were calculated and analyzed using paired *t*-tests. Effect sizes were reported as generalized eta square (η^2_G) for *F*-test and Hedge's *g* for *t*-test.

To explore potential associations between the repetition effect in Execution (ME), MI ability, and the vividness of MI with the repetition effect in Imagery (MI), Spearman's rank correlation coefficients were calculated. Specifically, correlations were examined between the repetition effects of Imagery and Execution across participants, as well as between the repetition effect of Imagery and various factors, including the kinesthetic imagery score on the cMIQ-R, visual imagery score on the cMIQ-R, the vividness of Imagery, and the adjusted vividness of Imagery (which accounts for individual differences in confidence levels). To prepare the equivalent sample set for correlation analysis after removing outliers, we identified multivariate outliers by calculating the Mahalanobis distance using all variables included in the correlation analysis. Any data points with Mahalanobis distances exceeding the 95% chi-square cutoff value were subsequently excluded from the analysis.

2.2 Results

2.2.1 RT results

Figure 2 shows the RTs of repetition and three different prime conditions from all participants and trials. The results of the two-way repeated-measures ANOVA revealed significant main effects and interactions. The main effect of Priming was significant, $F(2, 98) = 27.95$, $MSE = 0.11$, $p < 0.001$, $\eta^2_G = 0.12$. *Post-hoc* analyses indicated that participants had faster RT in the Execution (499 ms) than the Perception (558 ms) condition, $t(31) = -6.43$, $p < 0.001$, $g = -0.86$, and Imagery (566 ms) condition, $t(31) = -5.57$, $p < 0.001$, $g = -0.85$, but the Imagery and Perception conditions were not significantly different, $t(31) = 0.11$, $p = 0.916$. The main effect of repetition was significant, $F(1, 31) = 27.43$, $MSE = 0.07$, $p < 0.001$, $\eta^2_G = 0.04$, indicating that participants had faster RT in the repeat (515 ms) than the non-repeat (553 ms) condition. The two-way interaction was significant, $F(2, 98) = 27.39$, $MSE = 0.02$, $p < 0.001$, $\eta^2_G = 0.03$. *Post-hoc* analyses indicated that participants had faster RT in the repeat than non-repeat in the Execution condition, $t(31) = 8.01$, $p < 0.001$, $g = 1.11$, and Imagery condition, $t(31) = 4.55$, $p < 0.001$, $g = 0.47$, but not in the Perception condition, $t(31) = -0.51$, $p = 0.611$. In addition, the effect of repetition is larger in the Execution (70 ms) than the Imagery condition (52 ms), $t(31) = 2.32$, $p = 0.027$, $g = 0.33$.

2.2.2 Accuracies

Table 1 shows the results of accuracies. The results of the ANOVA revealed a significant main effect of priming condition on accuracy, $F(2, 98) = 5.95$, $MSE = 0.01$, $p = 0.005$, $\eta^2_G = 0.05$, indicating that participants' accuracies were lower in Perception (95.07%) than the Imagery (97.26%), $t(31) = -3.01$, $p = 0.015$, $g = -0.60$, and the Execution (96.89%), $t(31) = -2.60$, $p = 0.028$, $g = -0.49$, but not between Imagery and Execution, $t(31) = 0.62$, $p = 0.539$. However, there was no main effect of repetition, $F(1, 31) = 0.02$, $MSE = 0.00$, $p = 0.877$, and no interaction, $F(2, 98) = 2.05$, $MSE = 0.00$, $p = 0.148$.

2.2.3 Correlations among subjective vividness of MI and RT measures

When examining the correlations between subjective vividness and the repetition effect of Imagery, we introduced individual adjustments to the vividness ratings. This adjustment was based on each participant's self-estimated accuracy in the Execution condition. This approach aimed to address concerns related to individual differences in confidence when assigning subjective ratings. It is reasonable to assume that individuals who tend to either overrate or underrate their own performance in explicit tasks may similarly exhibit biases in evaluating the subjective vividness of their mental imagery experiences. Therefore, we calculated a confidence weight (CW) as the ratio between real accuracy and subjective accuracy to adjust the tendency in subjective ratings. Subsequently, we multiplied each participant's subjective ratings by their own CW to derive "adjusted vividness," which accounted for individual differences in aligning subjective ratings with observed performance.

After reviewing the data and identifying outliers using the multivariate Mahalanobis distance, we excluded two outliers before proceeding with the correlation analysis. The remaining dataset revealed the following correlations: the repetition effect of Imagery was positively correlated with repetition effect of Execution, $r = 0.60$, $p < 0.001$. However, the repetition effect of Imagery was not significantly correlated with the vividness, $r = 0.01$, $p = 0.978$, the adjusted vividness, $r = 0.05$, $p = 0.783$, or the visual imagery score of cMIQ-R, $r = -0.19$, $p = 0.319$, but was marginally correlated with kinesthetic imagery score of cMIQ-R, $r = -0.36$, $p = 0.052$.

2.3 Discussion

2.3.1 Repetition effect in MI

The presence of a significant repetition effect in the Imagery condition, but not in the Perception condition, highlights a crucial finding: mere stimulus repetition, without the engagement of actions through either physical execution or mental imagery, is insufficient to elicit the repetition effect. Importantly, the quicker RTs in repeat trials are not attributed to lower accuracy when compared to the RTs in non-repeat trials. In other words, the speed-accuracy trade-off cannot account for the more efficient response following the retrieval of the same S-R binding. This observation underscores the importance of S-R binding as a critical factor contributing to the repetition effect, in line with previous research (Pashler and Baylis, 1991; Henson et al., 2014).

Furthermore, the significant repetition effect observed during mental imagery, where muscle activations are not typically involved, suggests a central origin for this effect (Smith, 1968). This indicates

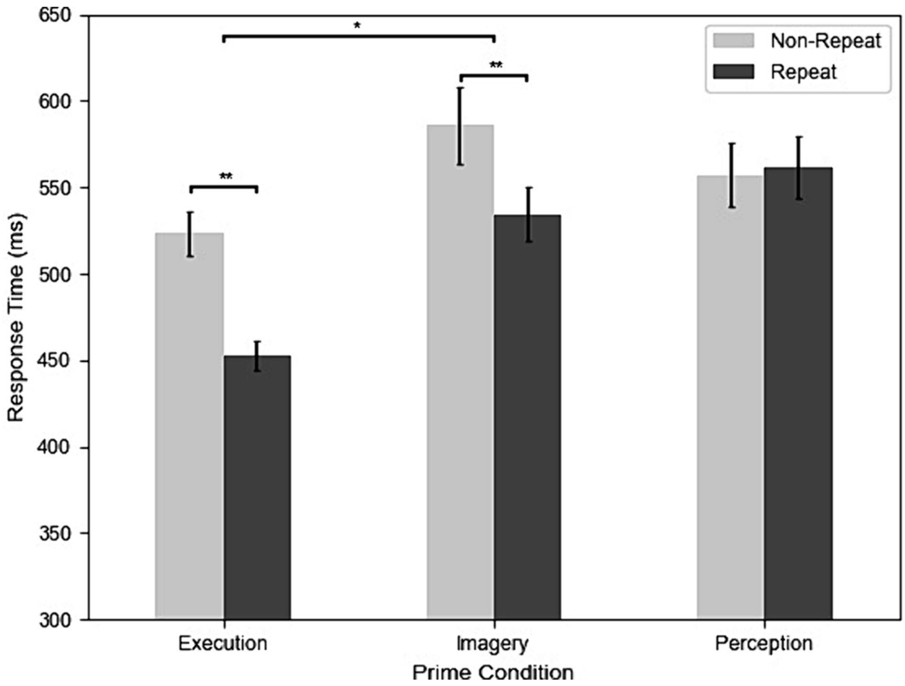


FIGURE 2
The results of response time (RT) across execution, imagery, and perception in repeated and non-repeated conditions. Error bars indicate the standard errors of each condition (*$p < 0.05$; **$p < 0.01$).

TABLE 1 Accuracies across execution, imagery, and perception in repeated and non-repeated conditions.

	Perception	Imagery	Execution
Repeated	94.3% (7.3%)	97.4% (4.1%)	97.6% (3.4%)
Non-repeated	95.8% (3.2%)	97.1% (3.3%)	96.2% (3.5%)

that the repetition effect can arise from mental simulation alone, without physical motor activity.

Moreover, the positive correlation between the repetition effects of MI and ME lends support to the notion that these two processes are related. However, it is important to note that the absence of EMG monitoring in the current experiment raises the possibility that some MI trials may have involved excessive muscle activities, potentially contributing to the observed repetition effect. This concern will be addressed and further clarified in Experiment 2.

2.3.2 Weaker repetition effect in MI than ME

Contrary to the expected outcome, MI showed a weaker repetition effect than ME. Several factors may contribute to the observed weaker repetition effect in the imagery condition: First, participants may engage in response suppression during mental imagery (Guillot et al., 2012), and this inhibitory process could potentially slow down the processing of subsequent responses or stimuli, thereby weakening the repetition effect (Rieger et al., 2017). Second, some participants reported during *post-hoc* interviews that, in the MI condition, they occasionally felt that the stimulus duration estimated from the color-response association phase was too short for them to complete the entire mental imagery process. It is plausible that mental imagery of rapid movements may require more time than its corresponding motor execution (Calmels et al., 2006), and insufficient programming time could impede the full development of the repetition effect in MI. Finally, ME involves both central planning and peripheral muscle activation. These two mechanisms may work in tandem to influence subsequent stimulus–response binding, potentially resulting in a stronger repetition effect.

3 Experiment 2: prolonged motor programming period and enhanced control with EMG recording

In Experiment 2, we intend to address a potential confounding factor associated with insufficient programming duration during the Imagery condition. This factor may have contributed to the observed weakening of the repetition effect in comparison to ME and thus affects how conclusion regarding the relationship between MI and ME are drawn. To mitigate this concern, we plan to extend the duration of prime responses in Experiment 2, thereby ensuring that MI can be programmed more comprehensively. Furthermore, in an effort to provide additional clarity and to verify that the repetition effect observed in MI during Experiment 1 was not influenced by subthreshold muscle contractions, we will implement a per-trial monitoring of EMG activity to assess muscle activation in Experiment 2. These methodological refinements will enable us to attain a more robust and comprehensive understanding of the distinct roles of MI and ME in motor repetition effects within the clear definition of MI in our study.

Hétu et al. (2013) have suggested that the occurrence of muscle contractions during imagined movements could introduce variability into neuroimaging responses. Therefore, EMG recording serves as a reliable measure to assess muscle activation during MI. By excluding trials in the Imagery prime condition that exhibited muscle activation in the EMG recordings, we aimed to uncover the repetition effect associated with clear MI which stemming from central processing without even tensing the muscle.

The extension of the prime response duration was crucial to ensure that participants had sufficient time for complete motor programming during MI. In Experiment 1, the brevity of the prime response duration may have limited the extent of motor planning in MI, potentially affecting the observed repetition effect. Therefore, in Experiment 2, we allowed participants more time for mental simulation and motor programming, ensuring that the MI condition was not constrained by time limitations.

The hypothesis driving Experiment 2 posited that if the repetition effect in MI is primarily a result of central cognitive processes and had been previously attenuated due to limited programming time, then a more pronounced and correlated repetition effect between MI and ME should be observable. The expectation was that these effects would remain consistent even after excluding trials with detectable muscle activity. These methodological enhancements in Experiment 2 were crucial for a deeper and more accurate understanding of the distinct roles and interactions of MI and ME in eliciting the repetition effect, all within the defined scope of our study's exploration of MI.

3.1 Materials and methods

3.1.1 Participants

In Experiment 2, a total of 51 participants were initially recruited. However, one participant had to be excluded from further data analysis due to technical issues with the EMG device during the experiment. Therefore, the completed dataset included 50 participants (24 males), with an age range of 18 to 26 years (M = 21.0 years). These participants were distinct from those who participated in Experiment 1. They were also selected from the student population of National Central University, Taiwan, and underwent screening to ensure the absence of known psychotic disorders or visual perception problems. All participants were right-handed, as evidenced by a mean score of 92.3 ± 12.1 on the Edinburgh Handedness Inventory – Short Form (Veale, 2014).

The study protocol received approval from the Research Ethics Committee of National Taiwan University. Prior to their participation, all individuals were provided with comprehensive explanations of the study procedures, their rights, and the potential risks associated with participation. Afterward, they voluntarily signed an informed consent form to participate in the study.

To estimate the sample size, we used data from the first six participants who were included after the process of EMG exclusion. We used G*Power (Faul et al., 2007) to target an effect size of *Cohen's* $d = 0.54$, based on the difference between repeated and non-repeated trials in the MI condition. The ideal power was set at 0.80, and the program estimated that 33 participants would be sufficient to reach an actual power of 0.80.

Following the EMG-trial exclusion process, a group of 33 participants (including 8 males) remained for further analysis. These individuals, ranging in age from 18 to 26 years with an average age of 21.2 years, exhibited a pronounced right-handed inclination, as indicated by a mean handedness score of 94.1 ± 10.5.

3.1.2 Design

The design of Experiment 2 closely mirrored that of Experiment 1, except for the number of trials. To account for expected trial drop-outs during the EMG-trimming process, participants in Experiment 2 completed three blocks of trials for each condition, resulting in a total of 108 trials per condition to ensure an adequate number of trials for analysis.

3.1.3 Task, stimuli, and apparatus

The task and equipment used in Experiment 2 largely replicated those of Experiment 1, with a few notable exceptions: To streamline the response interface and improve temporal precision, we replaced the gaming keyboard with a USB response pad (Black Box ToolKit 1–8 button) boasting a sampling rate of 50,000 Hz and a 25-ms key down duration. This response pad featured eight keys, corresponding to the index fingers, middle fingers, ring fingers, and little fingers of both hands.

Additionally, EMG data were recorded using strategically placed electrodes on the right flexor digitorum superficialis, with the ulna serving as the reference electrode and the medial epicondyle as the ground electrode.

For the first 32 participants, a wireless NeXus-10 device from MindMedia BV, Netherlands, was employed for EMG data collection, featuring a sampling rate of 2048 Hz. The EMG voltage values were captured using the Biotrace+ software, also from MindMedia B.V., Netherlands.

For the remaining participants, we utilized a BIOPAC MP36 machine to acquire the EMG signal. The EMG data was recorded and displayed using BIOPAC Student Lab 4.1 software, with a sampling frequency of 2000 Hz. This change in recording equipment was made to improve the signal-to-noise ratio.

It is important to note that the primary purpose of this EMG recording was for screening rather than for analyzing the EMG signal to generate critical results for the current experiment. Consequently, changing the recording device midway through the experiment could have potentially compromised the quality of screening and subsequently impacted the true positive rate of EMG activation detection.

3.1.4 Procedure

Experiment 2 largely followed the procedural framework of Experiment 1, with a notable alteration: the duration of the prime box was fixed at 800 ms for all priming conditions. This was a departure from Experiment 1, where the duration was either individually estimated (Perception and Imagery conditions) or remained onscreen until a response was executed (Execution condition).

3.1.5 Data analysis

The response exclusion criteria remained consistent with those used in Experiment 1. However, in the data preprocessing for Experiment 2, trials featuring EMG responses during the presentation of the prime boxes in the Perception and Imagery conditions were trimmed from the dataset. This was done to specifically evaluate the impact of muscle activation on the repetition effect of motor imagery.

Furthermore, the dataset without screened EMG responses was also analyzed to allow for comparisons with the results obtained in Experiment 1.

3.1.6 EMG preprocessing and analysis

In Experiment 2, the analysis of EMG signals data signals data underwent a two-fold process involving preprocessing and parameter adjustment to ensure the validity of muscle activation detection within each participant.

3.1.6.1 Signal down-sampling and filtering

Initially, the signals were down-sampled to 512 Hz from the NeXus-10 device recording and 500 Hz from the BIOPAC MP36 recording after applying an anti-aliasing filter. Subsequently, the EMG signals were subjected to band-pass filtering within the frequency range of 30 Hz to 55 Hz to focus on relevant muscle activity. To further refine the data, the power of the signals was computed by squaring them. Finally, a 10-point moving average was applied for signal smoothing, which aided in reducing noise and making the data more suitable for subsequent computing.

3.1.6.2 EMG response onset detection

The detection of EMG response onsets was a critical step in understanding the influence of muscle activation on the repetition effect. To achieve this, several statistics were calculated from baseline. The mean (M), standard deviation (SD), mean of the first derivative (dM), and standard deviation of the first derivative (dSD) were computed from a 200 ms interval before the prime boxes' presentation, serving as baseline. Then, two thresholds were set based on these statistics, utilizing two parameters: C_1 and C_2. If the EMG signal value exceeded $M + C1 \times SD$, and if the change in signal value exceeded $dM + C2 \times dSD$, the onset of the EMG response was marked. These criteria aimed to capture significant deviations from baseline muscle activity.

3.1.6.3 Optimization of parameters

To ensure the validity of the EMG response detection process, the optimal pair of parameters (C_1 and C_2) was determined individually for each participant. A comprehensive grid search approach was employed, with C_1 values ranging from 10 to 30 (in increments of 0.5) and C_2 values varying from 5 to 10 (also in increments of 0.5). The performance of each parameters pair was evaluated using 108 prime responses in the Execution condition (or 72 trials in the case of one participant due to a technical issue of trigger sending). Evaluation criteria included the distance between the EMG response onset and key press onset and the accuracy of EMG activation detection.

3.1.6.4 EMG detection accuracy

The performance assessment of parameters pairs centered on the accuracy of EMG activation detection. For each pair (designated as p), the accuracy (A_p) was computed as the ratio of correctly identified trials to the total number of trials. Correct trials were identified by detecting the EMG response onset before the key press onset. The paramount goal was to identify the parameter set that maximized the accuracy of EMG activation detection during the Execution condition.

3.1.6.5 Distance calculation and loss function

In addition to accuracy, the average distance (D_p) between the EMG-detected onset and the key press onset was calculated for each parameter pair (p) across all Execution prime trials. To holistically assess parameter performance, a loss function (L) was introduced, combining accuracy and temporal precision, defined as $L(C1,C2) = D_p \times 100^{A_p}$. This loss function provided a quantitative measure of how well a specific pair of parameters balanced accuracy and temporal alignment.

Ultimately, the EMG response detection criterion for each participant was thoughtfully determined by selecting the parameter pair that minimized the loss function within the Execution condition. Once this criterion was established, it was consistently applied to detect EMG responses in both the Perception and Imagery conditions.

3.1.6.6 Remaining participants post EMG-trial exclusion

The selection of participants for the EMG-trial-excluded group was contingent upon the parameters derived from their responses during the Execution condition. During this selection procedure, EMG-detected trials were systematically removed from both the Perception and Imagery conditions for each participant. Importantly, participants were excluded from this group only if the number of trial pairs, following the exclusion of EMG data, fell below eight in either sub-condition (e.g., Imagery-repeat).

The criteria for identifying EMG responses were individually established for each participant, guided by the C_1 and C_2 values. Remarkably, the average accuracy of EMG response detection during the Execution condition was 89%.

Participants in this group exhibited a mean of 78.15 remaining trials (with a standard deviation of 19.71) in the Perception condition and a mean of 67.97 remaining trials (with a standard deviation of 25.27) in the Imagery condition.

3.2 Results

3.2.1 The dataset without screened EMG responses

3.2.1.1 RTs

Figure 3 shows the RT of repetition and three different prime conditions from all participants and trials. The results of the RT analysis showed that all main effects and interactions were significant. The main effect of prime condition was significant, $F(2, 98) = 84.71$, $MSE = 0.30$, $p < 0.001$, $\eta^2_G = 0.25$. *Post-hoc* analyses indicated that participants had faster RT in Execution (447 ms) than Perception (554 ms), $t(49) = -11.29$, $p < 0.001$, $g = -1.45$, and Imagery (518 ms), $t(49) = -9.80$, $p < 0.001$, $g = -1.19$ and faster RT in Imagery than Perception, $t(49) = -4.42$, $p < 0.001$, $g = -0.43$. The main effect of repetition was significant, $F(1, 49) = 67.37$, $MSE = 0.13$, $p < 0.001$, $\eta^2_G = 0.07$, indicated that participants had faster RT in repeat (485 ms) than non-repeat (527 ms). The interaction between prime condition and repetition was also significant, $F(2, 98) = 45.31$, $MSE = 0.04$, $p < 0.001$, $\eta^2_G = 0.05$. *Post-hoc* analyses indicated that participants had faster RT in repeat than non-repeat in both Execution, $t(49) = 10.15$, $p < 0.001$, $g = 1.53$, and Imagery, $t(49) = 6.88$, $p < 0.001$, $g = 0.69$. However, this was not the case for the Perception condition, where the difference in RT between repetition and non-repetition was not significant, $t(49) = -0.75$, $p = 0.455$. In addition, the effects of repetition on RT was significantly larger in the Execution condition (77 ms) than the Imagery condition (54 ms), $t(49) = 3.05$, $p = 0.004$, $g = 0.41$.

After removing four outliers using multivariate Mahalanobis distance, we conducted a correlation analysis. The repetition effect of

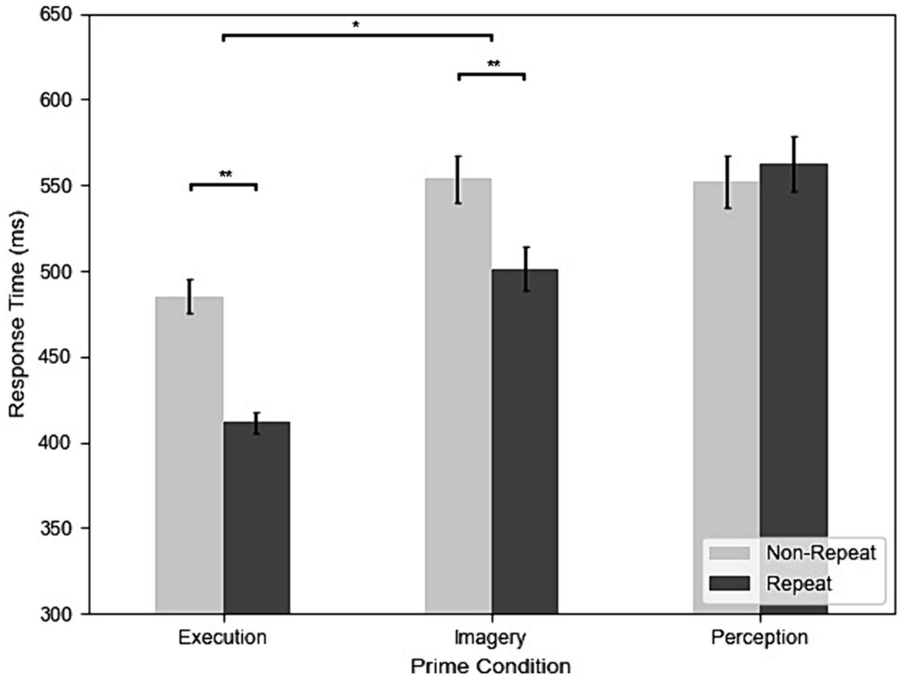


FIGURE 3
The results of response time (RT) across execution, imagery, and perception from the dataset without screened EMG responses (*$p < 0.05$; **$p < 0.01$).

Imagery was positively correlated with repetition effect of Execution, $r = 0.42$, $p = 0.003$, and the vividness, $r = 0.29$, $p = 0.046$. However, the repetition effect of Imagery was not significantly correlated with adjusted vividness, $r = -0.09$, $p = 0.561$, visual imagery score of cMIQ-R, $r = -0.01$, $p = 0.954$, or kinesthetic imagery score of cMIQ-R, $r = -0.17$, $p = 0.263$.

3.2.1.2 Accuracies

Table 2 shows the results of accuracies. There was a significant main effect of prime condition on accuracy, $F(2, 98) = 25.12$, $MSE = 0.04$, $p < 0.001$, $\eta^2_G = 0.13$. *Post-hoc* analyses indicated that participants had lower accuracy in Perception (94.4%) than the Execution (97.5%), $t(49) = 4.90$, $p < 0.001$, $g = 0.81$, and Imagery (97.7%), $t(49) = 5.75$, $p < 0.001$, $g = 0.84$. The difference in accuracy between Execution and Imagery was not significant, $t(49) = -0.67$, $p = 0.505$. There was no main effect of repetition, $F(1, 49) = 0.37$, $MSE = 0.00$, $p = 0.544$. However, there was a significant interaction, $F(2, 98) = 18.93$, $MSE = 0.01$, $p < 0.001$, $\eta^2_G = 0.06$. *Post-hoc* analyses indicated participants had higher accuracy in repeated pairs than non-repeated pairs in the Execution condition, $t(49) = -3.25$, $p = 0.004$, $g = -0.67$, and in Imagery condition, $t(49) = -2.48$, $p = 0.016$, $g = -0.43$. In the Perception condition, participants had lower accuracy for repeated pairs than non-repeated pairs, $t(49) = 3.04$, $p = 0.001$, $g = 0.44$.

3.2.2 EMG-trial-excluded group

3.2.2.1 RTs

In the analysis of RTs, the main effect of prime condition was found to be significant, $F(2, 64) = 57.92$, $MSE = 0.21$, $p < 0.001$, $\eta^2_G = 0.29$. *Post-hoc* analyses indicated that participants had faster RT in Execution (448 ms) than both the Perception (557 ms), $t(32) = -9.47$, $p < 0.001$, $g = -1.59$, and Imagery (527 ms), $t(32) = -8.37$, $p < 0.001$, $g = -1.38$. RTs in Imagery are also significantly faster than Perception, $t(32) = -2.89$, $p = 0.007$, $g = -0.37$. The main effect of repetition, $F(1, 32) = 40.20$, $MSE = 0.07$, $p < 0.001$, $\eta^2_G = 0.07$, indicated that participants had faster RT in repeat (492 ms) than non-repeat (530 ms). The interaction between prime condition and repetition was also significant, $F(2, 64) = 28.33$, $MSE = 0.03$, $p < 0.001$, $\eta^2_G = 0.06$. *Post-hoc* analyses indicated that participants had faster RT in repeat than non-repeat in both the Execution, $t(32) = 7.72$, $p < 0.001$, $g = 1.51$, and Imagery, $t(32) = 5.21$, $p < 0.001$, $g = 0.69$, but not in the Perception, $t(32) = -1.38$, $p = 0.176$. Furthermore, the repetition effect was significantly larger in the Execution condition (74 ms) than the Imagery condition (52 ms), $t(32) = 2.24$, $p = 0.032$, $g = 0.38$.

In the correlation analysis, none of the correlations were significant, including the repetition effect of Imagery and Execution, $r = 0.06$, $p = 0.728$, and the repetition effect of Imagery was not significantly correlated with measures of vividness, $r = 0.30$, $p = 0.100$, adjusted vividness, $r = 0.07$, $p = 0.682$, visual imagery score of cMIQ-R, $r = -0.03$, $p = 0.879$, or kinesthetic imagery score of cMIQ-R, $r = -0.26$, $p = 0.160$. One outlier was excluded from the analysis using the multivariate Mahalanobis distance.

3.2.2.2 Accuracies

The ANOVA on accuracy revealed a main effect of prime condition, $F(2, 64) = 11.70$, $MSE = 0.01$, $p < 0.001$, $\eta^2_G = 0.09$. *Post-hoc* analyses indicated that participants had lower accuracy in the Perception (95.6%) than the Imagery (98.0%) condition, $t(32) = 4.38$, $p < 0.001$, $g = 0.68$ and Execution (97.7%), $t(32) = 3.42$, $p = 0.003$, $g = 0.68$. Execution and Imagery conditions are not

TABLE 2 Accuracies across execution, imagery, and perception in repeated and non-repeated conditions in the dataset without screened EMG responses.

	Perception	Imagery	Execution
Repeated	93.1% (6.4%)	98.3% (2.7%)	98.4% (2.2%)
Non-repeated	95.6% (4.6%)	97.1% (3.0%)	96.5% (3.3%)

significantly different, $t(32) = -0.53$, $p = 0.603$. There was no significant difference in accuracy between the Execution and Imagery conditions, $F(1, 32) = 0.08$, $MSE = 0.00$, $p = 0.774$. The interaction between prime condition and repetition was significant, $F(2, 64) = 10.02$, $MSE = 0.01$, $p < 0.001$, $\eta^2_G = 0.05$. *Post-hoc* analyses indicated that accuracy had no significant difference in repeated pairs and non-repeated pairs in the Execution condition, $t(32) = -2.13$, $p = 0.081$, and in the Imagery condition, $t(32) = -0.67$, $p = 0.507$, $g = -0.03$. However, participants had lower accuracy in repeated pairs than non-repeated pairs in the Perception condition, $t(32) = 3.00$, $p = 0.016$, $g = 0.48$.

3.3 Discussion

In this experiment, we found that even after increasing the duration allowed for performing imagination, the repetition effect in Imagery remained weaker than that observed in Execution. This observation rules out the possibility that the weaker repetition effect in MI time was due to insufficient processing time allocated for mentally simulating motor actions. Moreover, even after excluding trials with excessive EMG activities, the repetition effect still persists in MI. This finding indicates that peripheral factors such as muscle activities cannot account for the repetition effect in MI, which strengthens the evidence for a central origin of repetition effect in MI.

An unexpected outcome here is the lack of significant correlation between the repetition effects of MI and ME. While previous research has often emphasized the overlap between these two modes of action, this result implies that the mechanisms governing the repetition effect in each mode may exhibit certain degree of autonomy. We shall address the possible relationships between MI and ME by considering findings and constraints of both experiments of the current study in the general discussion.

4 General discussion

To examine the relationship between MI and ME without reliance on self-report, we compared the repetition effects in both and found it weaker for the former. Furthermore, we also found that extending the duration of the prime stimuli in MI did not enhance its repetition effect but reduced the strength of correlation between the repetition effects in MI and ME. The inequivalent magnitude of repetition effects and the malleable correlation between MI and ME suggest that these two modes of action cannot be entirely equivalent (Jeannerod, 1995; O'Shea and Moran, 2017). The following discussion will consider potential mechanisms involved in the repetition effect and elucidate their roles in MI and ME.

4.1 The role of S-R binding in repetition effect

S-R binding is likely the mechanism underlying the repetition effect. However, unlike classical observations of repetition inhibition that are manifested as repetition costs (Rieger et al., 2017; Scheil and Liefooghe, 2018; Bart et al., 2021) we observed consistent repetition facilitation in both MI and ME. This suggests that the shared motor representation between the prime imagery and probe execution may have facilitated repeated responses. Two possible mechanisms for this facilitation are considered here:

First, during MI, the motor programming for responding to the prime stimulus may enhance short-term S-R binding (Ito, 1999; Liefooghe et al., 2021). This enhanced binding could result in faster retrieval when participants encounter the same stimulus again in the probe event, leading to faster responses in the repeated than non-repeated condition. Taken together with the lack of repetition effect in the Perception condition, it is likely that the construction of S-R binding during MI plays a pivotal role in the repetition effect.

Second, the interference from non-repeated prime responses may also contribute to the repetition effect. Some previous studies compared the priming effect of repeated and non-repeated MI with a neutral condition (e.g., rest or imagining both potential responses in prime) and found both the costs associated with alternative actions representation and benefits from repeated actions representation (Li et al., 2005; Ramsey et al., 2010; Toovey et al., 2021). The current findings lend support to the construction of stimulus–response binding during MI rather than counter-response interference as the primary factor contributing to the repetition effect. Specifically, when comparing MI with Perception, imagining actions associated with the prime did not result in slower probe responses than merely perceiving the prime when prime and probe were different, whereas repeated actions during MI prime resulted in faster probe responses than did merely perceiving the prime. The distinction between the Perception and MI conditions ruled out the interference account for the repetition effect.

One can take the probabilities of repetition and the orientation of attention into account when comparing the distinct RT patterns in the repeated vs. non-repeated prime-probe relationship for the Perception and MI conditions. In Toovey et al. (2021), the ratio of repeated to non-repeated pairs was 80:20, an unbalanced ratio that likely led participants to expect the same response after the prime. Consequently, when compared to the neutral condition, the lower predictive ratio hindered the response process in non-repeated probes. Moreover, their experimental design involved stimuli with two spatial orientations (e.g., left and right) corresponding to responses, which may have led to suppression of the opposite side when one's attention is already oriented toward the other direction (May et al., 1995). Similarly, Li et al. (2005) reported motor interference with MI when participants performed hand flexion and extension in their action priming paradigm. They found that motor interference from prime imagery occurred when the subsequent execution involved the contraction of antagonist muscles. Thus, interference may occur when alternative stimuli or responses in the choice set can induce suppression, either from opposite attention orientations or antagonist muscles.

The current study distinguished stimuli using colors instead of spatial orientation or the agonist–antagonist relationship. This color-based mapping is potentially less intuitive than mappings based on spatial or kinesthetic factors, which might explain the diminished suppression in the non-repeated prime response. This variation could contribute to the contrast in repetition facilitation observed in our study vs. the repetition inhibition reported in earlier research.

4.2 Stronger S-R binding in prime execution than prime imagery

Comparing repetition effects in the Imagery and Execution conditions of our study reveals that actual responses to prime stimuli foster more defined and specific motor processes. This leads to a more marked repetition effect than that observed in responses to prime Imagery. This observation is consistent with Toovey et al. (2021) findings which also employed a repetition paradigm to compare MI and MP (motor preparation, namely the motor planning phase before actual execution). Their study found a stronger repetition effect in MI compared to MP, implying that MI encompasses more comprehensive information, including sensory feedback predictions elicited by imagined movements. This detailed information likely forms a complex association with the stimulus, which is then reactivated when participants encounter the same stimulus subsequently. Incorporating this logic into our study, it is plausible to suggest that the genuine sensorimotor information involved in responding to the prime enhances the overlap in motor processes between the prime and the following probe, especially when an action is physically executed for the prime rather than merely imagined. The richer and more specific information obtained from processing and executing the prime likely prepares the effector system for the probe, consequently resulting in a stronger repetition effect.

Incomplete Overlap between the Motor Processes of MI and ME While the finding of repetition benefits in both Imagery and Execution conditions aligns with the notion of functional equivalence, which posits that these two conditions share similar underlying mechanisms, a stronger prediction of this theoretical perspective would entail a significant correlation between the repetition effects observed in these two conditions. In other words, individuals who exhibit a stronger repetition effect in prime Imagery should also demonstrate a correspondingly stronger repetition effect in prime Execution, reflecting the shared mechanisms between the two. However, in the current study, this prediction did not hold when we extended the response time for MI and excluded trials with muscle activation during MI. This discrepancy suggests that the relationship between repetition effects in Imagery and Execution may be more complex and influenced by nuanced factors.

What could be the non-overlapped parts between MI and ME? One possibility is that MI involves a higher degree of awareness and monitoring of motor processes than ME. Jeannerod (2001) proposed that cognitive states of simulated actions can vary along a spectrum of different levels of awareness. In our study, participants could evaluate and report the subjective vividness of their MI experiences, suggesting explicit and deliberate representations of the action. Moreover, previous neuroimaging studies assessing the explicitness, awareness, and attentiveness of MI have highlighted the involvement of the frontal–parietal network (Gerardin et al., 2000; Rushworth et al., 2003; Fridman et al., 2011; Lorey et al., 2011; Vry et al., 2012), which is also considered critical for motor awareness (Desmurget and Sirigu, 2009). The idea of conscious monitoring in MI concurs with the motor-cognitive model (Glover and Baran, 2017; Glover et al., 2020), which posits that MI and ME have distinct real-time control process. According to this framework, both MI and ME share common motor representations during pre-movement planning but diverge during real-time operations. MI requires conscious executive control processes, such as elaboration and monitoring, whereas ME can access online feedback without awareness (Johnson and Haggard, 2005; Cameron et al., 2009). This contrasts with the functional equivalence hypothesis which suggests that MI and ME involve similar mechanisms.

As our study required participants to perform a simple key-pressing response, they may have executed the key-pressing in an "auto-pilot" manner with limited conscious awareness of the movement process. During MI, avoiding deliberate processing awareness is challenging, even in simple key pressing tasks. Conversely, actual response execution can unfold quite automatically, involving minimal attention and awareness of the motor control process. This divergence in conscious awareness might account for the inconsistent correlation results observed between MI and ME in Experiment 1 and Experiment 2. In Experiment 1, the brief prime stimulus presentation may have expedited imagery, diminishing awareness of the imagery process and prompting more subliminal muscle activation. This uncontrolled muscle activation during MI leads to a similar processing pattern with ME. In contrast, the prolonged prime duration in Experiment 2 facilitated a smoother mental simulation of movements, allowing ample time to elaborate and monitor the motor control process during imagery. With controlled EMG activation, Experiment 2 indicates that the repetition effect in MI originates more purely from a central and top-down source, distinguishing it from ME. Our results align more closely with the motor-cognitive model, positing distinct online operations for Motor Imagery and Motor Execution, than with the functional equivalence hypothesis. We recommend that future research comparing MI and ME should evaluate not only their differences but also their covariation. While differences in MI and ME measures can highlight their dissimilarities, examining covariation can provide further understanding of the degree of overlap in their underlying processes.

4.3 Limitations

4.3.1 Accuracy of MI

Several limitations in the current study should be noted. MI is inherently a private and subjective process, and errors in MI can lead to trials being mistakenly categorized as repeated or non-repeated. Accurately measuring MI trial-by-trial without interfering with the task (e.g., requiring participants to report their accuracy after each trial) can introduce noise into the assessment of repetition effects in MI. To maintain equivalence across conditions, ME trials with incorrect responses to primes were not excluded from the analysis. However, given the high accuracies observed across participants in the ME condition, we believe the inferences drawn in this study remain valid.

4.3.2 Stimulus-driven vs. intention-driven action

In contrast to most studies on MI that have adopted subjective duration measurements, the current study generalizes the relationship between MI and ME in the simple visuomotor responses, which can be considered a type of stimulus-driven action (Herwig et al., 2007; Herwig and Waszak, 2012). Whether the conclusions regarding functional equivalence derived from this study extend to more complex, intention-driven types of movements remain to be clarified. Future research on after-effects of intention-based action (e.g., spontaneously selected key pressing) may offer valuable insights into the relationship between MI and ME in such contexts.

4.3.3 Incomparable response transition between MI and ME

In our study, participants alternated between responding with imagery and execution in the MI conditions, and between simply observing and executing in the Perception condition, but not in the ME condition. This mode-switching design might have contributed to the primary effect observed in the prime condition, where responses to the probe were faster in the ME condition compared to the MI and Perception conditions, regardless of repetition. Previous research has demonstrated that the binding between stimuli and responses can facilitate responses within the same mode but hinder switching between modes (Rieger et al., 2017; Scheil and Liefooghe, 2018). In their experiment, response times in MI were directly measured through motor responses initiated at the onset of MI, and they found that the same action could be facilitated when executed in the same response mode (e.g., ME-ME or MI-MI) but disrupted when switching between different response modes (e.g., MI-ME or ME-MI). However, our study aimed to investigate pure MI without requiring participants to indicate the onset of MI through indirect measures. This design aimed to prevent contamination of the motor representation of MI by pre- and post-motor responses. Future studies examining the differential magnitude of repetition effects between prime imagery and prime execution should consider the potential impact of mode-switching on the repetition effect and develop innovative methods to assess this influence.

4.3.4 Impacts of physical execution on imagery

Moreover, a notable aspect of our experimental design was the deliberate exclusion of "Imagery-Imagery" and "Execution-Imagery" pairs. This decision was primarily guided by the underlying logic of the repetition effect, which is central to our study. The repetition effect, as observed in motor control studies, typically manifests when the same action or task is repeated, leading to enhanced performance due to factors like priming, increased familiarity, and neural efficiency. In our experiments, we focused on "Imagery-Execution" and "Execution-Execution" pairs to directly assess this effect.

The "Imagery-Imagery" pair was excluded because repeating an imagined action without interspersing it with a physical execution would not have provided the contrast necessary to explore the primary aim of our study, which is to investigate the functional equivalence and relationship between MI and ME. Moreover, the repetition of imagery alone would likely fall short in demonstrating the cognitive and neural overlap between MI and ME, as our interest was in examining how imagined actions influence subsequent executed actions and vice versa.

Our study intentionally did not include the "Execution-Imagery" pairing as it diverges from our main objective, which was to explore how prior mental simulation (imagery) influences subsequent physical execution. Incorporating "Execution-Imagery" would have shifted the focus toward how physical execution primes mental simulation, deviating from our central theme. However, future research, particularly studies employing EEG/MEG or fMRI techniques, could benefit from including this pairing to investigate the covert neural processes involved, offering a different perspective on the interaction between executed actions and subsequent mental imagery.

5 Conclusion

Based on the findings of the current study, we have provided a method that may allow researchers to more objectively assess the impacts of MI on behavioral outcomes. By highlighting differences and the absence of correlation in repetition effects, this study challenges the functional equivalence hypothesis of imagery and execution. Our results suggest that motor representations of imagery and execution, when measured with responses that are not directly linked to the subjective aspects of the mental imagery, are more distinguishable than traditionally thought. The differential repetition effect between motor imagery and execution provide a methodological route for future studies aiming at examining cognitive and neural mechanisms of motor imagery under minimal impacts of subjective experiences.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://osf.io/b74ac/?view_only=96d7e4c10bac4923a96712980e9fbe31.

Ethics statement

The studies involving humans were approved by Research Ethics Committee of National Taiwan University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

H-PT: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. EC: Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. The research leading to these results received funding from Ministry of Science and Technology, ROC, under Grant Agreement MOST-106-2420-H-008-002-MY3 and MOST-108-2410-H-008-037-MY4.

Acknowledgments

We wish to express gratitude to Denise Hsien Wu who gave us numerous constructive comments. We also wish to thank members in Action & Cognition Laboratory and Concept & Language Laboratory for commenting the research.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Bart, V. K., Koch, I., and Rieger, M. (2021). Decay of inhibition in motor imagery. *Q. J. Exp. Psychol.* 74, 77–94. doi: 10.1177/1747021820949388

Bertelson, P. (1965). Serial choice reaction-time as a function of response versus signal-and-response repetition. *Nature* 206, 217–218. doi: 10.1038/206217a0

Brinkman, L., Stolk, A., Dijkerman, H. C., de Lange, F. P., and Toni, I. (2014). Distinct roles for alpha- and beta-band oscillations during mental simulation of goal-directed actions. *J. Neurosci.* 34, 14783–14792. doi: 10.1523/JNEUROSCI.2039-14.2014

Burianová, H., Marstaller, L., Sowman, P., Tesan, G., Rich, A. N., Williams, M., et al. (2013). Multimodal functional imaging of motor imagery using a novel paradigm. *NeuroImage* 71, 50–58. doi: 10.1016/j.neuroimage.2013.01.001

Cabral-Sequeira, A. S., Coelho, D. B., and Teixeira, L. A. (2016). Motor imagery training promotes motor learning in adolescents with cerebral palsy: comparison between left and right hemiparesis. *Exp. Brain Res.* 234, 1515–1524. doi: 10.1007/s00221-016-4554-3

Caligiore, D., Mustile, M., Spalletta, G., and Baldassarre, G. (2017). Action observation and motor imagery for rehabilitation in Parkinson's disease: a systematic review and an integrative hypothesis. *Neurosci. Biobehav. Rev.* 72, 210–222. doi: 10.1016/j.neubiorev.2016.11.005

Calmels, C., Holmes, P., Lopez, E., and Naman, V. (2006). Chronometric comparison of actual and imaged complex movement patterns. *J. Mot. Behav.* 38, 339–348. doi: 10.3200/JMBR.38.5.339-348

Cameron, B. D., Enns, J. T., Franks, I. M., and Chua, R. (2009). The hand's automatic pilot can update visual information while the eye is in motion. *Exp. Brain Res.* 195, 445–454. doi: 10.1007/s00221-009-1812-7

Decety, J., Jeannerod, M., Germain, M., and Pastene, J. (1991). Vegetative response during imagined movement is proportional to mental effort. *Behav. Brain Res.* 42, 1–5. doi: 10.1016/S0166-4328(05)80033-6

Decety, J., Jeannerod, M., and Prablanc, C. (1989). The timing of mentally represented actions. *Behav. Brain Res.* 34, 35–42. doi: 10.1016/S0166-4328(89)80088-9

Desmurget, M., and Sirigu, A. (2009). A parietal-premotor network for movement intention and motor awareness. *Trends Cogn. Sci.* 13, 411–419. doi: 10.1016/j.tics.2009.08.001

Duann, J.-R., and Chiou, J.-C. (2016). A comparison of independent event-related desynchronization responses in motor-related brain areas to movement execution, movement imagery, and movement observation. *PLoS One* 11:e0162546. doi: 10.1371/journal.pone.0162546

Faul, F., Erdfelder, E., Lang, A. G., and Buchner, A. (2007). G*power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* 39, 175–191. doi: 10.3758/BF03193146

Fridman, E. A., Desmurget, M., and Sirigu, A. (2011). “From conscious motor intention to movement awareness” in *Characterizing consciousness: From cognition to the clinic? Research and perspectives in neurosciences*. eds. S. Dehaene and Y. Christen (Berlin, Heidelberg: Springer).

Gentile, A. E., Rinella, S., Desogus, E., Verrelli, C. M., Iosa, M., Perciavalle, V., et al. (2024). Motor imagery for paediatric neurorehabilitation: how much do we know? Perspectives from a systematic review. *Front. Hum. Neurosci.* 18, 1245707. doi: 10.3389/fnhum.2024.1245707

Gentili, R., Cahouet, V., Ballay, Y., and Papaxanthis, C. (2004). Inertial properties of the arm are accurately predicted during motor imagery. *Behav. Brain Res.* 155, 231–239. doi: 10.1016/j.bbr.2004.04.027

Gerardin, E., Sirigu, A., Lehéricy, S., Poline, J. B., Gaymard, B., Marsault, C., et al. (2000). Partially overlapping neural networks for real and imagined hand movements. *Cereb. Cortex* 10, 1093–1104. doi: 10.1093/cercor/10.11.1093

Glover, S., and Baran, M. (2017). The motor-cognitive model of motor imagery: evidence from timing errors in simulated reaching and grasping. *J. Exp. Psychol. Hum. Percept. Perform.* 43, 1359–1375. doi: 10.1037/xhp0000389

Glover, S., Bibby, E., and Tuomi, E. (2020). Executive functions in motor imagery: support for the motor-cognitive model over the functional equivalence model. *Exp. Brain Res.* 238, 931–944. doi: 10.1007/s00221-020-05756-4

Goble, M. S. L., Raison, N., Mekhaimar, A., Dasgupta, P., and Ahmed, K. (2021). Adapting motor imagery training protocols to surgical education: a systematic review and Meta-analysis. *Surg. Innov.* 28, 329–351. doi: 10.1177/1553350621990480

Guillot, A., Di Rienzo, F., Macintyre, T., Moran, A., and Collet, C. (2012). Imagining is not doing but involves specific motor commands: a review of experimental data related to motor inhibition. *Front. Hum. Neurosci.* 6:247. doi: 10.3389/fnhum.2012.00247

Guillot, A., Hoyek, N., Louis, M., and Collet, C. (2012). Understanding the timing of motor imagery: recent findings and future directions. *Int. Rev. Sport Exerc. Psychol.* 5, 3–22. doi: 10.1080/1750984X.2011.623787

Hall, C. R., and Martin, K. A. (1997). Measuring movement imagery abilities: a revision of the movement imagery questionnaire. *J. Ment. Imag.* 21, 143–154,

Henson, R. N., Eckstein, D., Waszak, F., Frings, C., and Horner, A. J. (2014). Stimulus-response bindings in priming. *Trends Cogn. Sci.* 18, 376–384. doi: 10.1016/j.tics.2014.03.004

Herwig, A., Prinz, W., and Waszak, F. (2007). Two modes of sensorimotor integration in intention-based and stimulus-based actions. *Q J Exp Psychol (Hove).* 60, 1540–1554. doi: 10.1080/17470210601119134

Herwig, A., and Waszak, F. (2012). Action-effect bindings and ideomotor learning in intention- and stimulus-based actions. *Front. Psychol.* 3, 444. doi: 10.3389/fpsyg.2012.00444

Hétu, S., Grégoire, M., Saimpont, A., Coll, M. P., Eugène, F., Michon, P. E., et al. (2013). The neural network of motor imagery: an ALE meta-analysis. *Neurosci. Biobehav. Rev.* 37, 930–949. doi: 10.1016/j.neubiorev.2013.03.017

Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scand. J. Stat.* 6, 65–70,

Ito, M. (1999). Relation of repetition effect and response programming in a speeded choice task. *Percept. Mot. Skills* 88, 503–514. doi: 10.2466/pms.1999.88.2.503

Jeannerod, M. (1995). Mental imagery in the motor context. *Neuropsychologia* 33, 1419–1432. doi: 10.1016/0028-3932(95)00073-C

Jeannerod, M. (2001). Neural simulation of action: a unifying mechanism for motor cognition. *NeuroImage* 14, S103–S109. doi: 10.1006/nimg.2001.0832

Johnson, P. (1982). The functional equivalence of imagery and movement. *Quarterly J. Experimental Psychol. Section A.* 34, 349–365. doi: 10.1080/14640748208400848

Johnson, H., and Haggard, P. (2005). Motor awareness without perceptual awareness. *Neuropsychologia* 43, 227–237. doi: 10.1016/j.neuropsychologia.2004.11.009

Li, S., Stevens, J. A., Kamper, D. G., and Rymer, W. Z. (2005). The movement-specific effect of motor imagery on the premotor time. *Mot. Control.* 9, 119–128. doi: 10.1123/mcj.9.2.119

Liefooghe, B., Jim, A., and De Houwer, J. (2021). Automatic effects of covert practice. *Q J Exp Psychol (Hove).* 74, 1697–1708. doi: 10.1177/17470218211007138

Lin, C.-H. (2011). Development of the Chinese movement imagery questionnaire-revision. *Sports & Exercise Res.* 13, 289–300. doi: 10.5297/ser.1303.008

Lindsay, R. S., Larkin, P., Kittel, A., and Spittle, M. (2023). Mental imagery training programs for developing sport-specific motor skills: a systematic review and meta-analysis. *Phys. Educ. Sport Pedagog.* 28, 444–465. doi: 10.1080/17408989.2021.1991297

Lorey, B., Pilgramm, S., Bischoff, M., Stark, R., Vaitl, D., Kindermann, S., et al. (2011). Activation of the parieto-premotor network is associated with vivid motor imagery—a parametric fMRI study. *PLoS One* 6:e20368. doi: 10.1371/journal.pone.0020368

Lotze, M., Montoya, P., Erb, M., Hülsmann, E., Flor, H., Klose, U., et al. (1999). Activation of cortical and cerebellar motor areas during executed and imagined hand movements: an fMRI study. *J. Cogn. Neurosci.* 11, 491–501. doi: 10.1162/089892999563553

Louis, M., Collet, C., and Guillot, A. (2011). Differences in motor imagery times during aroused and relaxed conditions. *J. Cogn. Psychol.* 23, 374–382. doi: 10.1080/20445911.2011.521739

Malouin, F., Richards, C. L., Durand, A., and Doyon, J. (2008). Reliability of mental chronometry for assessing motor imagery ability after stroke. *Arch. Phys. Med. Rehabil.* 89, 311–319. doi: 10.1016/j.apmr.2007.11.006

May, C. P., Kane, M. J., and Hasher, L. (1995). Determinants of negative priming. *Psychol. Bull.* 118, 35–54. doi: 10.1037/0033-2909.118.1.35

Monteiro, K. B., Cardoso, M. S., Cabral, V. R. C., Santos, A. O. B., Silva, P. S., Castro, J. B. P., et al. (2021). Effects of motor imagery as a complementary resource on the rehabilitation of stroke patients: a Meta-analysis of randomized trials. *J. Stroke Cerebrovasc. Dis.* 30:105876. doi: 10.1016/j.jstrokecerebrovasdis.2021.105876

Morone, G., Ghanbari Ghooshchy, S., Pulcini, C., Spangu, E., Zoccolotti, P., Martelli, M., et al. (2022). Motor imagery and sport performance: a systematic review on the PETTLEP model. *Appl. Sci.* 12:9753. doi: 10.3390/app12199753

Munzert, J., Lorey, B., and Zentgraf, K. (2009). Cognitive motor processes: the role of motor imagery in the study of motor representations. *Brain Res. Rev.* 60, 306–326. doi: 10.1016/j.brainresrev.2008.12.024

O'Shea, H., and Moran, A. (2017). Does motor simulation theory explain the cognitive mechanisms underlying motor imagery? A critical review. *Front. Hum. Neurosci.* 11, 72. doi: 10.3389/fnhum.2017.00072

Page, S. J., Levine, P., Sisto, S., and Johnston, M. V. (2001). A randomized efficacy and feasibility study of imagery in acute stroke. *Clin. Rehabil.* 15, 233–240. doi: 10.1191/026921501672063235

Papaxanthis, C., Pozzo, T., Kasprinski, R., and Berthoz, A. (2003). Comparison of actual and imagined execution of whole-body movements after a long exposure to microgravity. *Neurosci. Lett.* 339, 41–44. doi: 10.1016/S0304-3940(02)01472-6

Paravlic, A. H., Slimani, M., Tod, D., Marusic, U., Milanovic, Z., and Pisot, R. (2018). Effects and dose–response relationships of motor imagery practice on strength development in healthy adult populations: a systematic review and Meta-analysis. *Sports Med.* 48, 1165–1187. doi: 10.1007/s40279-018-0874-8

Pashler, H., and Baylis, G. C. (1991). Procedural learning: II. Intertrial repetition effects in speeded-choice tasks. *J. Exp. Psychol. Learn. Mem. Cogn.* 17, 33–48. doi: 10.1037/0278-7393.17.1.33

Pfurtscheller, G., and Neuper, C. (1997). Motor imagery activates primary sensorimotor area in humans. *Neurosci. Lett.* 239, 65–68. doi: 10.1016/S0304-3940(97)00889-6

Posner, M. I. (1980). Orienting of attention. *Q. J. Exp. Psychol.* 32, 3–25. doi: 10.1080/00335558008248231

Posner, M. I. (2005). Timing the brain: mental chronometry as a tool in neuroscience. *PLoS Biol.* 3:e51. doi: 10.1371/journal.pbio.0030051

Ramsey, R., Cumming, J., Eastough, D., and Edwards, M. G. (2010). Incongruent imagery interferes with action initiation. *Brain Cogn.* 74, 249–254. doi: 10.1016/j.bandc.2010.08.005

Reed, C. L. (2002). Chronometric comparisons of imagery to action: visualizing versus physically performing springboard dives. *Mem. Cogn.* 30, 1169–1178. doi: 10.3758/BF03213400

Ridderinkhof, K. R., and Brass, M. (2015). How kinesthetic motor imagery works: a predictive-processing theory of visualization in sports and motor expertise. *J. Physiol.-Paris.* 109, 53–63. doi: 10.1016/j.jphysparis.2015.02.003

Rieger, M., Dahm, S. F., and Koch, I. (2017). Inhibition in motor imagery: a novel action mode switching paradigm. *Psychon. Bull. Rev.* 24, 459–466. doi: 10.3758/s13423-016-1095-5

Rieger, M., and Gauggel, S. (1999). Inhibitory after-effects in the stop signal paradigm. *Br. J. Psychol.* 90, 509–518. doi: 10.1348/000712699161585

Rushworth, M. F. S., Johansen-Berg, H., Göbel, S. M., and Devlin, J. T. (2003). The left parietal and premotor cortices: motor attention and selection. *NeuroImage* 20, S89–S100. doi: 10.1016/j.neuroimage.2003.09.011

Sapien, R. E., and Rogers, R. G. (2010). "The use of motor imagery in teaching surgical skills lessons from sports training" in *The neurophysiological foundations of mental and motor imagery*. eds. A. Guillot and C. Collet (Oxford: Oxford University Press). 245–252.

Scheil, J., and Liefooghe, B. (2018). Motor command inhibition and the representation of response mode during motor imagery. *Acta Psychol.* 186, 54–62. doi: 10.1016/j.actpsy.2018.04.008

Sidaway, B., and Trzaska, A. (2005). Can mental practice increase ankle dorsiflexor torque? *Phys. Ther.* 85, 1053–1060. doi: 10.1093/ptj/85.10.1053

Smith, M. C. (1968). Repetition effect and short-term memory. *J. Exp. Psychol.* 77, 435–439. doi: 10.1037/h0021293

Tamir, R., Dickstein, R., and Huberman, M. (2007). Integration of motor imagery and physical practice in group treatment applied to subjects with Parkinson's disease. *Neurorehabil. Neural Repair* 21, 68–75. doi: 10.1177/1545968306292608

Toovey, B. R. W., Seiss, E., and Sterr, A. (2021). Functional equivalence revisited: costs and benefits of priming action with motor imagery and motor preparation. *J. Exp. Psychol. Hum. Percept. Perform.* 47, 1698–1716. doi: 10.1037/xhp0000966

Van Selst, M., and Jolicoeur, P. (1994). A solution to the effect of sample size on outlier elimination. *Quarterly J. Experimental Psychol. Section A.* 47, 631–650. doi: 10.1080/14640749408401131

Veale, J. F. (2014). Edinburgh handedness inventory - short form: a revised version based on confirmatory factor analysis. *Laterality* 19, 164–177. doi: 10.1080/1357650X.2013.783045

Verbruggen, F., Logan, G. D., Liefooghe, B., and Vandierendonck, A. (2008). Short-term aftereffects of response inhibition: repetition priming or between-trial control adjustments? *J. Exp. Psychol. Hum. Percept. Perform.* 34, 413–426. doi: 10.1037/0096-1523.34.2.413

Vry, M. S., Saur, D., Rijntjes, M., Umarova, R., Kellmeyer, P., Schnell, S., et al. (2012). Ventral and dorsal fiber systems for imagined and executed movement. *Exp. Brain Res.* 219, 203–216. doi: 10.1007/s00221-012-3079-7

Wearden, J. H. (2003). Applying the scalar timing model to human time psychology: Progress and challenges. In *Time and mind II: Information processing perspectives*. ed. H. Helfrich. (Ashland, OH, US: Hogrefe & Huber Publishers), 21–39.

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 05 June 2024
DOI 10.3389/fpsyg.2024.1355381

OPEN ACCESS

EDITED BY
Sabine Schaefer,
Saarland University, Germany

REVIEWED BY
Eduardo Nicoliche,
Federal University of Rio de Janeiro, Brazil
Jennifer Lehmann,
University of Regensburg, Germany

*CORRESPONDENCE
Thomas Jürgen Klotzbier
✉ thomas.klotzbier@inspo.uni-stuttgart.de

RECEIVED 13 December 2023
ACCEPTED 16 May 2024
PUBLISHED 05 June 2024

CITATION
Klotzbier TJ and Schott N (2024) Mental rotation abilities of gymnasts and soccer players: a comparison of egocentric and object-based transformations. An exploratory and preliminary study.
Front. Psychol. 15:1355381.
doi: 10.3389/fpsyg.2024.1355381

Mental rotation abilities of gymnasts and soccer players: a comparison of egocentric and object-based transformations. An exploratory and preliminary study

Thomas Jürgen Klotzbier* and Nadja Schott

Institute of Sport and Movement Science, Department of Sport Psychology and Human Movement Performance, University of Stuttgart, Stuttgart, Germany

Background and objectives: The experience obtained from motor expertise may contribute to and enhance the development of particular visuo-spatial abilities. This exploratory and preliminary study compares the response times of a mental rotation task with egocentric and object-based transformation instructions between soccer players of varying performance levels and gymnasts.

Methods: Fifty-six male participants were grouped based on their sports experience. Soccer-specific novices (SS-N: n = 19; age = 15.9 ± 0.87), soccer-specific experts (SS-E: n = 17; age = 16.4 ± 0.70), gymnastic-specific experts (GS-E: n = 10; age = 16.6 ± 1.71), and gymnastic-specific novices (GS-N: n = 10; age = 16.0 ± 1.63) were recruited to perform a perceptual task (recognition of soccer-specific poses) and mental rotation tasks with different stimuli (soccer-specific poses, cubes, line-drawings of hands, letters).

Results: During the perceptual task with instructions on egocentric transformation and soccer-specific poses, we observed that gymnasts had longer response times than soccer players. Our findings also suggest that experts correctly identified most of the poses in terms of accuracy. In the mental rotation task with object-based transformation, gymnasts processed all stimuli, even the soccer-specific poses, more accurately than both soccer groups.

Conclusion: Our results suggest that gymnasts' motor expertise plays a role in their performance on mental rotation tasks involving both egocentric and object-based transformations, regardless of the stimuli presented.

KEYWORDS
mental rotation, soccer players, gymnasts, perceptual task, motor expertise, spatial ability

1 Introduction

Mental rotation, the ability to mentally represent and manipulate objects, is crucial in daily situations requiring spatial reasoning (Uttal et al., 2013b). Spatial orientation and imagination are essential skills in various professions, including car mechanics, electricians, graphic designers, and physicians (Ha and Fang, 2016; Sorby et al., 2021). Spatial cognition and appropriate motor skills are essential for athletic performance in a sport-specific context (Moreau et al., 2011). Especially in ball games such as soccer or basketball, spatial cognitive abilities are essential to anticipate actions from the offense or defense from different views (Mann et al., 2007; Voss et al., 2010; Ben Mahfoudh and Zoudji, 2022).

Spatial perception, spatial visualization, and mental rotation are recognized as key components of spatial cognition (Linn and Petersen, 1985). However, more recent research has identified additional distinctions between spatial abilities (Holden et al., 2015; Buckley et al., 2018). The study by Buckley et al. (2018) highlights a lack of precise definition and categorization of spatial abilities, recommending the integration of current research findings to address this gap. Mental rotation describes the ability to manipulate two mentally- or three-dimensional objects with respect to their orientation, i.e., to rotate, mirror, or tilt them (Shepard and Metzler, 1971). The term also refers to a paradigm or a specific experimental design that has become increasingly popular in neuropsychological research in recent years. Shepard and Metzler (1971) first described mental rotation as involved in object recognition. They operationalized it using what is now referred to as the classical mental rotation task and measured the response time required to solve the task. Participants were given "mirror-normal discrimination tasks" (Cooper and Shepard, 1973; Cooper, 1975) in which they compared objects. Then, they were required to decide equality and inequality (same-different judgment), irrespective of a possible angular disparity between the comparison objects. The dependent variables measured were the time from the beginning of the stimulus presentation to the response – usually pressing a button – and accuracy. Therefore, Shepard and Metzler's tests can be described as chronometric tests.

Shepard and Metzler (1971) studied response times when recognizing unfamiliar objects. Their classical study involved the use of three-dimensional (3D) cube figures. The participants were presented with paired images of these cube figures, which were rotated by different angular degrees either in the depth or image planes. The task was to determine as quickly as possible whether the objects could be merged by rotation or not. Shepard and Metzler demonstrated that the response time depends on the angular disparity between the two cubes. That is, the response time increased linearly with increasing angular disparity. However, when the angular disparity between the target and the comparison figure exceeds 180°, there is no further linear increase in response times. This finding is commonly interpreted to suggest that the mental rotation process is analogous to an actual executed rotation. This post-hoc explanation of the time characteristic is based on data obtained through participant introspection in these experiments. The participants reported that they imagined the object in 3D space and were thus able to rotate the object around any axis.

However, a distinction is made between two transformation strategies in mental rotation tasks: an object-based and egocentric (perspective) transformation, which can induce concise tasks and specific instructions (Zacks et al., 2002). How individuals solve a mental rotation task depends on the type of judgment that needs to be made (Steggemann et al., 2011). The former (object-based) requires same-different judgments with respect to pairs of stimuli, while the latter (egocentric) requires left-right judgments with a single stimulus (Feng et al., 2017). Cohen and Kubovy (1993) defined two criteria that must be met to refer to an object-based mental rotation. The first criterion is a positive slope, meaning that the greater the angular disparity between the two objects being compared, the longer it takes to complete the task. Thus, the correlation between response time and degree of rotation is characterized by a monotonically increasing trend up to 180°. The second criterion is the maximum rotation speed, which must not be exceeded. The upper limit of the response time must remain undetermined until the determinants of the rotation process are known. Cooper (1975) discussed another criterion that best reflects the basic idea of mental rotation. The third criterion is the parity decision: Participants will be assigned to make a parity decision. A mental rotation process only occurs if there is an angular difference between the two objects being compared. Participants must determine whether the two objects are identical.

Numerous studies suggest a significant connection between mental rotation and spatial thinking, with motor abilities playing an essential part in both areas (Moreau et al., 2011). Mental rotation is an important aspect of spatial thinking and is associated with mathematical progress and educational achievement (Bott et al., 2023). Additionally, this cognitive skill is closely linked to motor abilities, as evidenced by the impact of motor limitations on mental rotation in children (Krúger and Krist, 2009). The link between spatial cognition and motor skills is further highlighted by the relationship between motor skills and executive functions, which are vital for spatial problem-solving (Stuhr et al., 2020). Theories of embodied perception emphasize the role of interaction between action and cognition (Kiefer and Trumpp, 2012). Several studies have shown that there is a correlation between perceptual ability and motor expertise within the respective domain. Blake and Shiffrar (2007) argue that motor expertise plays a crucial role in the perception of human movement. Markman and Brendl (2005) found that the movement-compatibility effect is influenced by self-representation in space, highlighting the complex interplay between perceptual and motor representations. Beilock (2008) further supported this by demonstrating the pivotal role of sensorimotor experience in embodied cognition. Eskenazi et al. (2009) provided neuropsychological evidence showing that neurological impairments can affect performance and action perception, suggesting a close link between the two. Hohmann et al. (2011) furthered this research by showing that motor expertise can influence action and actor recognition, with experts demonstrating faster reaction times and greater accuracy. These studies underscore the correlation between perceptual ability and motor expertise within their respective domains.

The findings of Proffitt et al. (1995) and Bhalla and Proffitt (1999) also support this approach, indicating that an observer's physiological potential to climb a hill affects their perception of its slope. This suggests a close link between visual perception and an observer's motor preconditions and expertise. Expert observers in sports and other domains of visual expertise possess the remarkable ability to quickly and accurately determine the key characteristics of motion (Dicks et al., 2019). This ability is developed through encounters with the same classes of movement, allowing experts to recognize them (Sparrow and Sherman, 2001). Kaltner et al. (2014) suggest that mental rotation performance is not only influenced by motor expertise but also by visual expertise. Furthermore, specific sports training that involves extensive mental rotation ability can significantly enhance mental rotation performance (Moreau, 2012).

These findings highlight the strong connection between spatial cognition, motor skills, and sports performance.

Research has demonstrated that individuals with motor expertise have an advantage of this very expertise when performing mental rotation tasks (Jansen and Lehmann, 2013; Habacha et al., 2014, 2022; Schmidt et al., 2016; Weigelt and Memmert, 2021; Kamruddin, 2022). For instance, Habacha et al. (2014) conducted a study comparing table tennis players, who frequently perform and observe rapid hand movements, with soccer players, who lack experts in hand movements, in a mental rotation task using their hands. The authors found that table tennis players exhibited faster mental rotation of their hands and had lower response times for object-based transformations. This study highlights the embodied nature of the mental rotation task of hands by showing selective effects of motor expertise. The study by Jansen and Lehmann (2013) examined the effects of motor expertise on mental rotation tasks involving cube figures and human poses. The study included 40 participants in each group: soccer players, gymnasts, and non-athletes. The study found that all participants had a higher mental rotation accuracy for human poses than cubes. In addition, gymnasts demonstrated better mental rotation performance than non-athletes. Only gymnasts who had practiced rotation movements around the three axes performed better in the mental rotation task, irrespective of the type of stimuli. Soccer players did not perform statistically better than non-athletes. In their meta-analysis, Voyer and Jansen (2017) examined the moderating effects of the relationship between motor expertise and performance on spatial tasks. The authors showed that concerning the type of sport, ball sports have only a small effect, while gymnastics has a medium effect on mental rotation abilities. It is important to emphasize that the study grouped gymnasts and dancers into one gymnastics category. However, when gymnasts and dancers were analyzed separately, very different effect sizes emerged. Gymnasts alone exhibited a high effect size (Cohen's d) of 0.516 (95% CI = 0.184, 0.938), whereas dancers showed a very small effect of $d = 0.057$ (95% CI = −0.396, 0.509). Weigelt and Memmert (2021) investigated the extent to which the expertise of basketball players accounts for differences in performing mental rotation tasks. The authors observed better mental rotation performance in experts compared to novices.

Previous studies have neglected whole-body rotations and more complex movements (e.g., symmetrical or asymmetrical arm, leg, trunk, or head movements in certain sport-specific skills) in mental rotation tasks (Heinen, 2013). Heinen, therefore, poses the question of whether more complex whole-body rotations have similar effects on mental rotation performance as (relatively simple) hand movements or human line drawings/poses.

Therefore, in the present exploratory and preliminary study, we used the images of body postures that occur in sports movements (soccer-specific skills/poses) rather than regular movements (e.g., arm stretching) to understand better the interplay between sports expertise and the egocentric transformation in mental rotation tasks. Unlike Jansen and Lehmann (2013), we examine soccer players and gymnasts; however, we used more complex whole-body soccer-specific human poses and additional stimuli to compare the two groups directly in one study.

Thus, in the first perceptual task with soccer-specific poses, we want to 1) examine whether soccer-specific poses are egocentrically transformed and show a linear trend between reaction time and angular disparity. If we do not observe a linear trend, we can assume an egocentric transformation and rule out the possibility of a mental rotation process. A key aspect of this perceptual task is to 2) investigate whether soccer players can identify soccer-specific poses faster and more accurately than gymnasts due to their greater familiarity with these types of stimuli. In a second mental rotation task with object-based transformations (poses, cubes, hands, letters), we will 3) investigate whether there is a linear trend (a very well-established finding) between response time and angular disparity when mentally rotating these stimuli. This approach allows us to test whether these stimuli are indeed subject to mental rotation. Our central objective is to 4) analyze whether experts in gymnastics or soccer players can mentally rotate object-based, soccer-specific poses faster and more accurately than their respective novices.

We hypothesized that soccer players would recognize soccer-specific poses more quickly than gymnasts in the perceptual task with egocentric transformation, while the experts would perform best. We expect a linear trend for the mental rotation tasks with object-based transformation, especially for cubes, with cube figures taking the longest to make a parity decision (see Jansen and Lehmann, 2013). We expect that gymnasts will recognize soccer-specific poses faster when they are presented rotated by different degrees around the X, Y, and Z-axes and when a parity decision (same-different judgement) is required.

2 Materials and methods

2.1 Participants

All participants were recruited at sports clubs through telephone requests by the investigator. The soccer experts (SS-E group) were male players from the German Youth Bundesliga. The soccer novices (SS-N group) were recruited from various soccer clubs in the district league (7th league, Baden-Württemberg). The gymnastics groups (GG-E, GG-N) were recruited from several clubs in the Baden-Wuerttemberg region, where gymnastics is mainly performed at the national and regional levels. Participants were included if they agreed to participate in the study. In this regard, it is a random selection of participants within the groups described above. Athletes had to be in good health and actively trained at the specified national and regional levels to be eligible.

Participation in the exploratory and preliminary study was voluntary, and participants received no financial compensation. They gave their written and verbal informed consent to participate in the study and were informed of the content and procedure of the study. None of the participants had previously participated in an experiment involving mental rotation tasks.

2.2 Stimulus material for the perceptual task with egocentric transformation

Smith Micro's Poser® Version 8 3D graphics software was used to design the soccer-specific poses (see **Figure 1** and **Supplementary Material A**). These poses, familiar to soccer players, show (1) an instep drive, a typical attacking position used

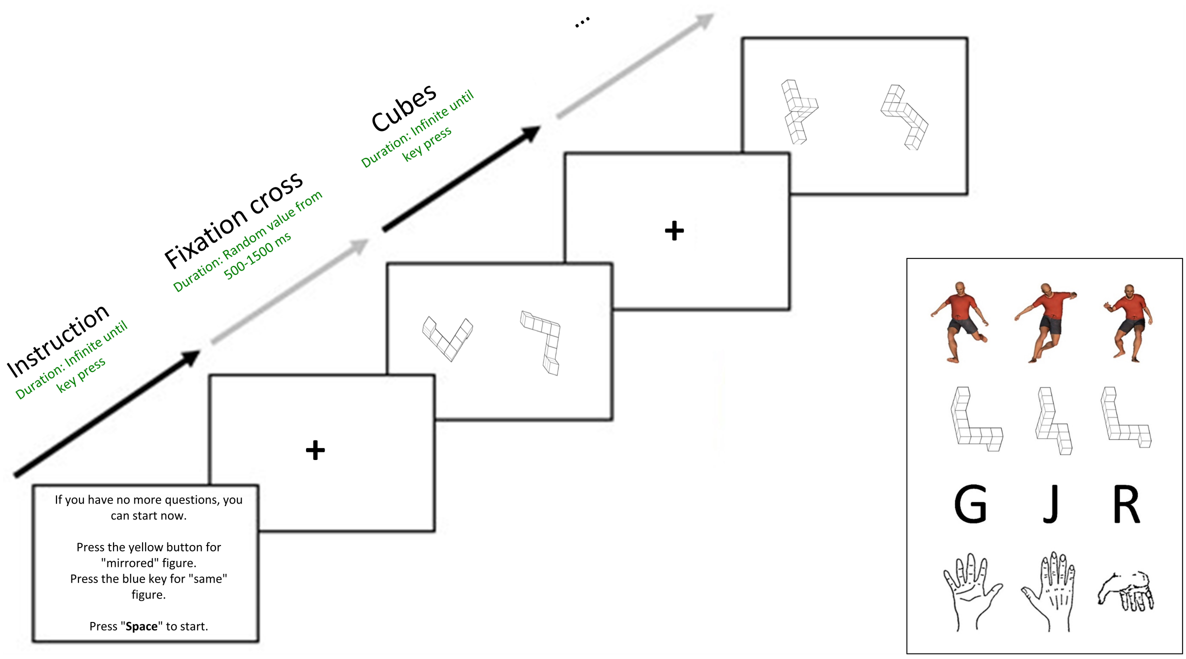


FIGURE 1
Sequence of the mental rotation experiment in E-Prime® using the example of the task with cubes.

to score a goal; (2) a cross ball, also called a fly ball; and (3) an inside kick, as used in passing.

The three poses, their mirroring, and the rotations (80°, 160°, 240°, and 320°) around the Z axis (vertical axis) were used (see **Supplementary Material A**; 3 poses × 2 reflection × 4 rotation angles × 1 axis "Z"). Thus, one cycle contains 24 poses/trials. These 24 poses were presented in three cycles: 24 poses × 3 cycles = 72 poses/trials. Participants were instructed to decide whether the soccer-specific pose depicted a human figure trying to kick the ball with the right or left leg as quickly as possible.

2.3 Stimulus material for the mental rotation task with object-based transformation

The mental rotation tasks' stimuli consisted of identical or mirrored figures presented simultaneously and side by side. In all mental rotation tasks, participants had to follow an object-based instruction and decide as quickly as possible whether the two presented stimuli were the same or different, making as few errors as possible, regardless of their rotation in space (80°, 160°, 240°, and 320° in the X, Y, and Z axes).

In the mental rotation tasks, soccer-specific poses, cube figures, letters, and line drawings of hands were used (see **Figure 1** and **Supplementary Materials B–E**). The different poses and cubes were presented in a randomized order and rotated around the X (horizontal), Y (transverse), and Z (vertical) axes. The letters and hands were also randomized and presented with rotations around the Z-axis only. The target figure of all stimuli (poses, cubes, hands, letters) was always presented in a 40° position (see **Supplementary Materials B–E**). The comparison figures were presented simultaneously in 80°, 160°, 240°, and 320° positions, side by side with the target figure. **Figure 2** shows the angle that must be rotated to transform the comparison figure into the target figure. The angles selected in this way can be used to determine whether mental rotation is involved in processing the stimuli. If RT of 80° < RT of 320° < RT of 160° < RT of 240°, then mental rotation can be assumed due to the linear function (see **Figure 2**). This function also implies the ability to identify the shortest path for mental rotation (Takano, 1989).

We used the soccer-specific poses already used in the simple perceptual task shown in **Figure 1** for the mental rotation task. The target pose and a comparison pose with different angular positions were presented simultaneously and side by side (see **Supplementary Materials B, F**; 3 poses × 2 reflection × 4 rotation angles × 3 axis "X, Y and Z"). A cycle of soccer-specific poses thus contains 72 trials. These 72 trials were presented in three cycles: 72 trials × 3 cycles = 216 trials.

The cubes for this exploratory and preliminary study were taken from the "Mental Rotation Stimulus Collection" by Peters and Battista (2008). This collection consists of 16 different stimuli, their reflections, and orientations from 0° to 360°, each with 5° angle variations. Three cubes from this collection were randomly selected (see **Figure 1**). An example of a cube with four orientations around the X–axis can be found in **Supplementary Material C** (3 cubes × 2 reflections × 4 rotation angles × 3 axes "X, Y and Z"). A cycle with cubes thus contains 72 trials. These 72 trials were presented in three cycles: 72 trials × 3 cycles = 216 trials.

The letters used are G, J, and R and their reflections (see **Figure 1**). Other studies have already used these letters (Cooper and Shepard, 1973; Kail et al., 1980). These letters are 2D and only presented in rotation around one axis (Z-axis) (see **Supplementary Material D**; 3 letters × 2 reflection × 4 rotation angles × 1 axis

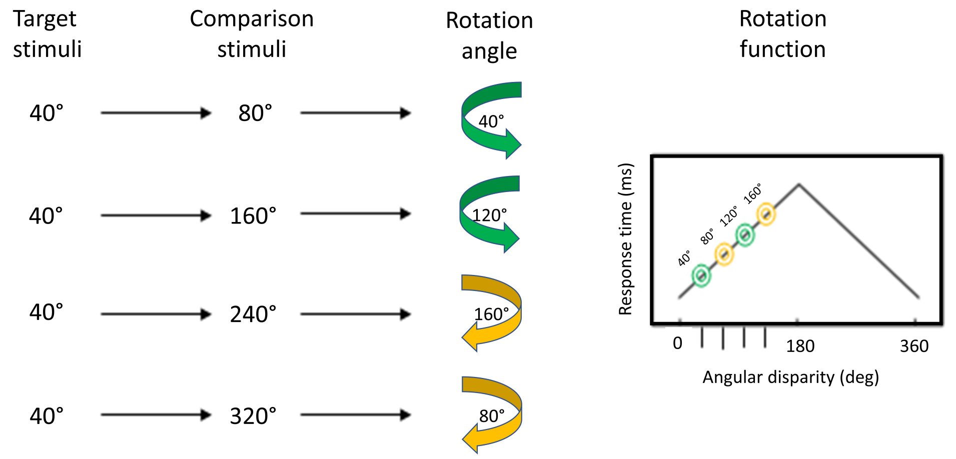


FIGURE 2
Schematic representation of the rotation function and the angles to be mentally rotated. The green (counterclockwise) and yellow (clockwise) arrows above the angle to be rotated indicate the shortest path of a rotation. For a 320° position of the comparison figure, one of the two figures (target or comparison figure) must be rotated by 80°.

"Y"). A cycle with letters thus contains 24 trials). These 24 trials were presented in three cycles: 24 trials × 3 cycles = 72 trials.

The hands selected were those used in the experiments by Parsons (1987) and, a few years later, by Lameira et al. (2008). These are line drawings of three different hand positions (palm, back of the hand, and wrist; see **Figure 1**). These hands are 2D and presented only in rotation around one axis (Z-axis) (see **Supplementary Material E**; 3 hands × 2 reflection × 4 rotation angles × 1 axis "Y"). A cycle with hands thus contains 24 trials. These 24 trials were presented in three cycles: 24 trials × 3 cycles = 72 trials.

2.4 Experimental setup and procedure

The experiment was conducted using a notebook with a 17.3" display and the presentation software E-Prime®. For this purpose, a program structure was developed in E-Prime® to run the blocks and stimuli sequentially and to record the response times and the response accuracy. The blocks were presented in a randomized order, similar to the corresponding stimuli. The respective stimuli with a size of 8cm were presented on a white background. The participants used their index fingers to type their answers on two keys of the notebook keyboard. The answer key "x" (German keyboard layout) positioned on the left and the answer key "m" placed on the right were each color-coded (yellow for "same" or "left" and blue for "different" or "right"; depending on the task to be performed). The choice of the index finger was motivated by the need for standardized data collection and response time recording. Selecting the index finger could potentially minimize variability across participants (Yang et al., 2003), given that it is a commonly preferred and frequently used finger for various tasks (Cavina-Pratesi and Hesse, 2013). This approach aims to promote more uniform data collection across the study population. Annett and Annett (1979) illustrated that in tasks involving simple and choice reaction times, responses tended to be faster when alternating between fingers on different hands rather than those on the same hand. Furthermore, no discernible effects were noted based on hand preference or gender. Conversely, some researchers employ the left and right mouse clicks as response options (Kaltner et al., 2014; Pietsch et al., 2019). The experiment was conducted in a quiet room. The rooms were kept dark during the test phase to avoid light reflections on the screen.

The task was to respond to the stimuli as quickly as possible by pressing the correct key. The participants completed a short practice block after reading the instructions in E-Prime®. The practice blocks were designed to familiarize the participants with the stimuli and tasks and consisted of 10 practice trials for each stimulus and task. The test was not started until the practice block was completed with an accuracy of 66.6% (2/3 correct responses). If 66% was not achieved, the practice block was repeated. A short 5-min break was taken between the test blocks. The total test duration was approximately 60–80 min, depending on individual response times.

2.5 Statistical analyses

E-DataAid® was used for initial data inspection. Using E-Basic, the programming language underlying E-Prime®, a program command was written to filter the response times of correct trials (ms) and accuracy (%). Similar to Jost and Jansen (2020), reaction times were analyzed for rotated trials but not for trials in which the comparison stimuli were mirrored. Data was then analyzed using SPSS version 29.0 (SPSS Inc., Chicago, Illinois). R was used to graph the results (Wickham, 2016; R Core Team, 2023).

First, we examined the response times and accuracy for missing values, normality of distributions (tested by Kolmogorov–Smirnov tests), and the presence of outliers. An alpha level of 0.05 was used for all statistical tests. Group comparisons for continuous variables (such as age and BMI) were assessed using ANOVAs; categorical demographic variables were compared using Chi-Square. Effect sizes for all ANOVAs were reported using Partial Eta Square ($\eta^2 p$)

(Lakens, 2013), with a small effect defined as 0.01, a medium effect as 0.06, and a large effect as 0.14 (Cohen, 1988).

A power analysis (Superpower; Caldwell and Lakens, 2019) was conducted on a 2x2x4 ANOVA with repeated measures design with 10 participants per cell (16 cells in our design). Assuming a medium effect size of $f = 0.2828$ (according to Brysbaert (2019), p. 7), an effect size of $d = 0.4$ is considered interesting, as it has practical relevance; $f = (0.4 / \sqrt{2})$, a standard deviation of 1.0, and a correlation of 0.2 [an effect size of $d = 0.4$ corresponds to a correlation of $r = 0.2$; Brysbaert (2019), p. 7], and with an alpha of 0.05, a power of 100% was found for the main effect of group, a power of 100% for the main effect of expertise, a power of 96.3% for the main effect of angle, a power of 6.1% for the interaction effect of group × expertise, 4.7% for the interaction effect of group × angle, 6.2% for expertise × angle, and 5.9% for the three-way interaction of group × expertise × angle. Due to the limited power for detecting interaction effects within our analyses, we can only provide reliable statements regarding the main effects, which aligns with the recommendation made by Brysbaert (2019).

We also conducted additional analyses to assess the impact of speed-accuracy trade-offs. Specifically, we examined the response time data to determine whether faster responses were associated with decreased accuracy, which could suggest a trade-off. For this purpose, bivariate correlations were calculated between each stimulus's average reaction times and the respective stimulus's average accuracy.

2.5.1 Analysis of the perceptual task with egocentric transformation

Bivariate correlations with the variables reaction time and rotation angle (40°, 80°, 120°, and 160°; see **Figure 2**) were calculated to show a linear trend in the egocentric-based transformation (same - different judgment) between angular disparity and reaction time. The larger the angular disparity between the two objects of comparison, the longer the response times. A monotonically increasing trend characterizes the relationship between response time and degree of rotation. Mental rotation can be assumed for linear trends and monotonic slopes (Cohen and Kubovy, 1993). Studies indicate that both "live matches" and "TV matches" impact the perception and performance of soccer skills (Bruland and van der Kamp, 2012), aligning with embodied perception theory (Shiffrar and Heinen, 2011, 2015). Pizzera and Raab (2012) delved deeper into the influence of motor and visual experience on decision-making among sports officials, emphasizing their significant role in perception. These findings emphasize the intricate connection between live/TV matches and sports-specific skill perception, with embodied perception theory playing a central role. For this reason, these factors were included as covariates to control for their confounding influence.

A 2 (sports: gymnastics and soccer) × 2 (expertise: experts and novices) × 4 (angle: 80°, 160°, 240°, and 320°) repeated measures ANCOVAs were performed for the mean response times at all rotation angles with each stimulus as the dependent variable and group as the fixed factor with "live matches" and "TV matches" as covariates (since not only motor expertise but also visual experience plays an important role in mental rotation performance; Kaltner et al., 2014) to examine group differences in the processing of the perceptual task with soccer-specific poses.

2.5.2 Analysis of the mental rotation task with object-based transformation

Bivariate correlations with the variables reaction time and rotation angle (40°, 80°, 120°, and 160°; see **Figure 2**) were calculated to show a linear trend in the object-based transformation (same - different judgment) between angular disparity and reaction time.

A 2 (sports: gymnastics and soccer) × 2 (expertise: experts and novices) × 4 (angle: 80°, 160°, 240°, and 320°) repeated measures ANOVA was performed to examine the group difference in reaction times of the mental rotation task with soccer-specific poses, cubes, letters, and hands (within-subject factors).

3 Results

3.1 Sample characteristics

Fifty-six participants (all male, age = 16.2 ± 1.12) voluntarily participated (see **Table 1** for participant characteristics). The participants were divided into the following groups depending on their sports activity: Concerning soccer-specific sports experience, two experimental groups were formed. The soccer-specific expert (SS-E) group ($n = 17$; age = 16.4 ± 0.70) is playing for the B - junior team of a Bundesliga club, with a high soccer-specific expertise. The second group of soccer players ($n = 19$; age = 15.9 ± 0.87) is called soccer-specific novices (SS-N) since they have a significantly lower training volume and play in a lower league. The participants were asked to complete a questionnaire about their sports biography to obtain these characteristics. In addition, a third and a fourth group with gymnastics-specific experts (GS-E; $n = 10$; age = 16.6 ± 1.71) and gymnastics-specific novices (GS-N; $n = 10$; age = 16.0 ± 1.63) participated in the exploratory and preliminary study. The gymnasts competed mainly in the Swabian Gymnastics Federation.

Concerning the age of starting regular training, there was an expertise main effect ($F(1,52) = 6.65$, $p = 0.013$, $\eta^2_p = 113$) and a sports × expertise interaction effect ($F(1,52) = 4.75$, $p = 0.034$, $\eta^2_p = 0.084$). The SS-E started regular training significantly earlier than all other groups. Concerning the amount of training, the expertise groups differed significantly ($F(1,52) = 120$, $p < 0.001$, $\eta^2_p = 698$). Experts had a higher training volume compared to the novices. The difference in training volume between experts and novices was higher for the soccer players than for the gymnasts ($F(1,52) = 16.4$, $p < 0.001$, $\eta^2_p = 239$).

In addition to active sports, the additional involvement with soccer is also of particular interest. Overall, soccer players watch more live games and more games on TV compared to gymnasts. No expertise effect was found.

3.2 Results for the perceptual task with egocentric transformation

The bivariate correlation between angular disparity and response time ($r = -0.08$) showed no significant linear trend ($p = 0.249$). In contrast, the bivariate correlation between angular disparity and accuracy showed a significant linear trend ($r = 0.179$,

TABLE 1 Characteristics of SS-E, SS-N, GS-E, and GS-N, including mean values (standard deviation) and an inferential statistical comparison of the groups.

	SS-E (n = 17)	SS-N (n = 19)	GS-E (n = 10)	GS-N (n = 10)	Stat. analyses
Age (years, SD)	16.4 (0.70)	15.9 (0.87)	16.6 (1.71)	16.0 (1.63)	$F(3,51) = 0.85$, $p = 0.472$, $\eta^2_p = 0.048$
BMI (kg/m^2)	22.6 (1.37)	21.4 (1.85)	20.6 (2.64)	20.9 (2.65)	$F(3,49) = 3.17$, $p = 0.032$, $\eta^2_p = 0.162$
Live soccer matches (%)					$CHI^2(9) = 54.6$, $p < 0.001$
None	0	0	80.0	60.0	
1 match	0	0	10.0	30.0	
2–4 matches	17.6	36.8	10.0	10.0	
More than 4 matches	82.4	63.2	0	0	
TV soccer matches (%)					$CHI^2(9) = 40.9$, $p < 0.001$
0 min	0	0	50.0	50.0	
1–60 min	11.8	10.5	40.0	50.0	
61–120 min	23.5	31.6	10.0	0	
More than 120 min	64.7	57.9	0	0	
Age at onset with regular training (years, SD)	5.29 (1.05)§	7.68 (2.65)^{ŧ}	6.40 (1.17)	6.40 (1.17)	$F(3,52) = 5.30$, $p = 0.003$, $\eta^2_p = 0.234$
Training duration per week (min)	763 (90.3)$^{§,\$,\#}$	267 (63.9)$^{ŧ,\$}$	569 (183)$^{ŧ,§,\$}$	340 (156)$^{ŧ,\$}$	$F(3,52) = 59.3$, $p < 0.001$, $\eta^2_p = 0.774$
Greatest sports success (all sports)					$CHI^2(8) = 31.8$, $p < 0.001$
No competitive activity	0	5.3	0	0	
Local competitions	0	10.5	0	0	
Regional competitions	5.9	52.6	70.6	80.0	
National competitions	23.5	26.3	20.0	10.0	
International competitions	70.6	5.3	10.0	10.0	

ŧ significant difference to SS-E ($p < 0.05$); § significant difference to SS-N ($p < 0.05$); $ significant difference to GS-E ($p < 0.05$); # significant difference to GS-N ($p < 0.05$).

$p = 0.07$). The correlations examining the Accuracy-Speed trade-offs reveal no significant relationships ($r = 0.01$, $p = 0.997$). An ANCOVA for response accuracy, controlled for live and televised soccer games, and the independent variables sports and expertise showed no significant effects for the main effect angular disparity or the interactions with the sports group and expertise group (see Figure 3 right graph). Only the between-subjects effect expertise showed an overall significant effect ($F(1,48) = 4.31$, $p = 0.044$, $\eta^2_p = 0.086$), with experts (86.0 ± 10.2) achieving higher overall accuracy than novices (80.1 ± 10.0). An ANCOVA for reaction time, controlled for live and televised soccer games, and the independent variables sports and expertise showed a significant interaction for angular disparity by sports ($F(2.30,110) = 8.03$, $p < 0.001$, $\eta^2_p = 0.143$). RTs did not differ in angular disparity for soccer players but for gymnasts (see Figure 3 left graph). In addition, there was a significant interaction between angle disparity and watching live soccer matches ($F(2.30,110) = 4.95$, $p = 0.006$, $\eta^2_p = 0.093$). Overall, people watching two or more games were equally fast for different angles. In contrast, those watching only one or no game were slower overall and showed higher RTS with increasing angle disparity. The between-subjects effect sports showed an overall significant effect ($F(1,50) = 8.71$, $p = 0.005$, $\eta^2_p = 0.154$), with soccer players (1479 ± 465) reacting faster than gymnasts (2119 ± 1091).

3.3 Results for the mental rotation task with object-based transformation

The bivariate correlations between the angle to be rotated and the response times indicated a linear trend, with $r = 0.233$, $p < 0.001$ for the poses, $r = 0.190$, $p < 0.001$ for the cubes, $r = 247$, $p < 0.001$ for the hands, and $r = 0.169$, $p = 0.011$ for letters (see Figure 4).

The bivariate correlations between the angle to be rotated and the accuracy indicated a linear trend, with $r = -0.217$, $p = 0.05$ for the poses, $r = -0.216$, $p < 0.05$ for the cubes, and $r = -0.177$, $p = 0.008$ for letters. No linear trend for hands ($r = -0.129$, $p = 0.054$) could be observed (see Figure 5). The correlations examining the Accuracy-Speed trade-offs reveal no significant relationships for poses ($r = 0.252$, $p = 0.061$), however a significant correlation for letters ($r = 0.428$, $p < 0.01$), hands ($r = 0.275$, $p = 0.040$) and cubes ($r = 596$, $p < 0.001$).

The 2 (sports: gymnastics and soccer) × 2 (expertise: experts and novices) × 4 (angle: 80°, 160°, 240°, and 320°) for accuracy

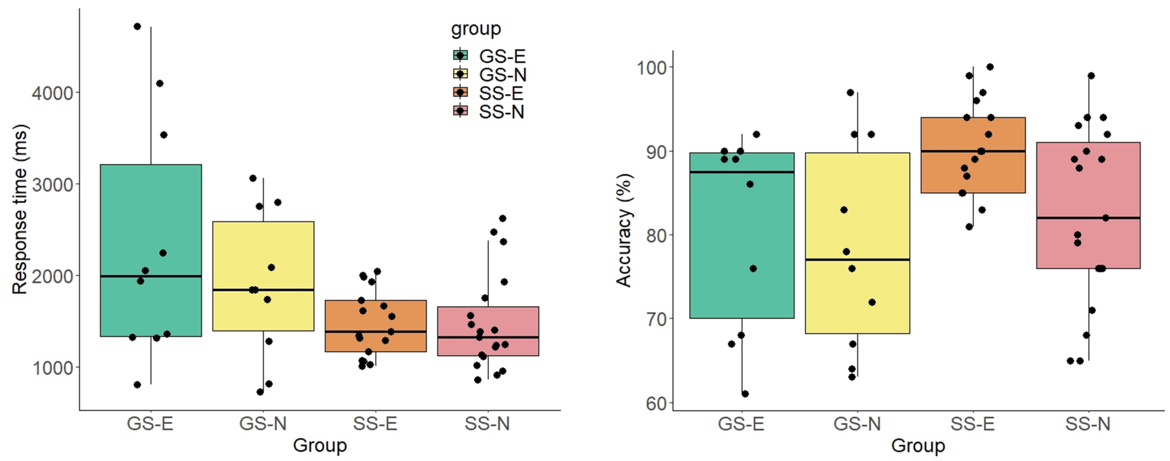


FIGURE 3
RT and accuracy (mean and standard error) as a function of angular disparity for mental rotation of soccer poses with egocentric transformation.

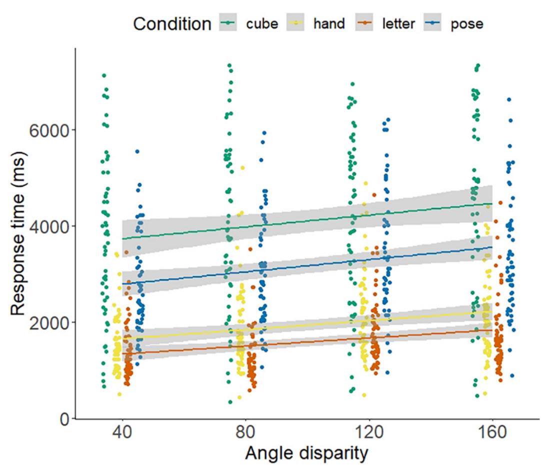


FIGURE 4
Linear trend between the response time (ms) and the angle to be rotated (disparity) separated by stimuli and groups. Linear fitting cures and individual data points. Angle disparity describes the angle to be rotated up to the target figure.

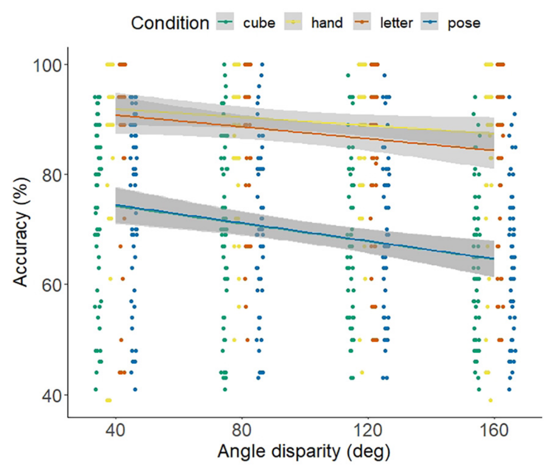


FIGURE 5
Linear trend between the accuracy and the angle to be rotated (disparity) separated by stimuli and groups. Linear fitting cures and individual data points. Angle disparity describes the angle to be rotated up to the target figure.

as well as RT of soccer poses showed a main effect for angle disparity, with the highest accuracy for the 80° condition and the longest RTs for 160° and 240°. No significant interactions between angle disparity and sports or expertise were observed. The between-subjects effect sports showed an overall significant effect ($F(1,52) = 6.05$, $p = 0.017$, $\eta^2_p = 0.104$) for accuracy, with soccer players (77.1 ± 16.2) achieving lower overall accuracy than gymnasts (87.3 ± 10.2).

The 2 (sports: gymnastics and soccer) × 2 (expertise: experts and novices) × 4 (angle: 80°, 160°, 240°, and 320°) ANOVA with repeated measures for accuracy, as well as RT of cubes, showed a main effect angle disparity, with the highest accuracy for the 80° condition and the longest RTs for 240°. No significant interactions for angle disparity with sports or expertise were observed. The between-subjects effect sports showed an overall significant effect ($F(1,52) = 20.0$, $p < 0.001$, $\eta^2_p = 0.278$) for accuracy, with soccer players (63.8 ± 13.0) achieving lower overall accuracy than gymnasts (79.2 ± 10.3).

The 2 (sports: gymnastics and soccer) × 2 (expertise: experts and novices) × 4 (angle: 80°, 160°, 240°, and 320°) ANOVA with repeated measures for accuracy as well as RT of letters showed a main effect angle disparity with the highest accuracy for the 80° and the 320° condition and the longest RTs for 160° and 240°. Furthermore, there were significant interactions for RT between angle disparity and sports and expertise. Soccer players had significantly higher RTs than gymnasts, especially for the angular degrees 160 and 240; experts, in turn, had higher RTs, especially for the angular degrees 240 and 320. The between-subjects effect sports showed an overall significant effect ($F(1,43) = 10.2$, $p = 0.003$, $\eta^2_p = 0.192$), with soccer players (1811 ± 935) reacting slower than gymnasts (1378 ± 594).

The 2 (sports: gymnastics and soccer) × 2 (expertise: experts and novices) × 4 (angle: 80°, 160°, 240°, and 320°) ANOVA with repeated measures for accuracy as well as RT of hands showed a main effect angle disparity, with the highest accuracy for the 80° condition and the longest RTs for 160° and 240°. No significant interactions for disparity with sports or expertise were observed. The between-subjects effect sports showed an overall significant effect ($F(1,47) = 9.34$, $p = 0.003$, $\eta^2_p = 0.175$), with soccer players (2060 ± 681) reacting slower than gymnasts (1514 ± 489).

The inferential statistical results of the ANOVAs are presented in **Table 2**. **Figures 6**, **7** show the results for RT and accuracy of the mental rotation tasks separated by stimuli and group.

4 Discussion

The exploratory and preliminary study aimed to compare the mental rotation performance of gymnasts and soccer players of different expertise levels. Given this study's limited number of cases, it is advisable to interpret the results with caution. Particularly due to our small sample size and limited statistical power regarding the interaction effects, definitive conclusions cannot be drawn (refer to Brysbaert, 2019, p. 27). This should be considered when interpreting the results and in the subsequent discussion.

Soccer-specific poses were utilized in the initial perceptual task, requiring participants to make right-left decisions. The study assessed whether this task induces an egocentric transformation and whether differences are present among the groups. We found no significant correlation between response time and angular disparity, suggesting no object-based transformation was involved. We also found no significant differences in accuracy or response times between the groups. Nonetheless, SS-E displayed increased response accuracy and consistent response times compared to both groups. On the other hand, GS-E displayed the longest response times, which was consistent with our expectations.

In a second mental rotation task, participants were asked to determine parity (judging whether the figures were the same or different) between a target and a comparison figure using various stimuli such as cubes, poses, letters, and line drawings of hands. The purpose was to evaluate whether this task resulted in an object-based transformation (indicated by a linear trend between response time and angular disparity) and whether the groups exhibited discrepancies based on the stimuli. The significant correlation among response times for cubes, hands, and poses suggests that a parity decision prompted an object-based transformation, specifically for unfamiliar cube figures. However, we cannot detect a significant positive linear trend between response time and angular disparity for letters, indicating that they are not mentally rotated. A group effect is observed in response times and accuracy for cubes, drawings of hands, and soccer-specific poses, with the GS-E group exhibiting advantages. Gymnasts were quicker to perceive all stimuli and had lower response times. Even in soccer-specific poses, gymnasts perceived stimuli faster when presented around various axes. Notably, the results of the experts show that orientation in space is of greater importance than the specific pose. When presented upside down, gymnasts perceive soccer-specific poses faster than soccer players. However, soccer players do not recognize soccer-specific poses faster when presented upside down. Mental rotation of letters is not observed, as no positive linear trend between response time and angular disparity nor any group differences are evident.

Athletes have accumulated significant sensory and motor expertise through years of training and performing diverse activities and skills (O'Regan and Noë, 2001; Blake and Shiffrar, 2007). This expertise leads to neurophysiological and psychological modifications in various body systems, resulting in a sensorimotor system that differs considerably from non-athletes (Tomasino et al., 2013). Thus, mental rotation performance is expected to differ depending on the sensorimotor and psychomotor characteristics of individuals with varying levels of sports-specific expertise. Moreau et al. (2012) instructed their participants to complete a mental rotation test before and after engaging in specific physical training. While mental rotation ability was observed for one activity (wrestling), it was not observed for the other (running). The results indicate that the wrestling group performed better than the running group in the mental rotation test following the physical training. This suggests that adaptations resulting from the training affected mental rotation performance.

Embodied cognition theory asserts that physical movement and motor imagery share a common process, as Wohlschläger and Wohlschläger (1998) explain. Advocates of embodied cognition propose that the organism's sensory and motor systems are dynamically integrated. This concept is called sensorimotor coupling, which facilitates the efficient use of sensory information during action. Embodied cognitive perspectives have the potential to inform and influence research on motor skills in the domains of sports and sports psychology (Beilock, 2008). Research findings have revealed that the embodiment hypothesis operates in numerous ways in sport-related contexts, including action-specific perception, comprehension, prediction, and decision-making (Calvo-Merino et al., 2005; Casile and Giese, 2006; Moreau et al., 2011, 2012). Action-specific perception, also known as perception-action, is a psychological theory that posits that individuals perceive their environment based on their ability to act (Proffitt, 2006; Witt, 2011). Numerous studies have documented action-specific effects across various contexts (Witt and Proffitt, 2008). The action-specific perception account supports the idea that perception involves processes linking the environment/objects and the perceiver's capability for action. Similar objects or environments, such as specific soccer poses, including full-span kicks, cross balls, and inside kicks used in passing, appear different depending on the observer's abilities. As these abilities change over time and with experience, an individual's perception of comparable objects and environments will similarly change. Soccer players, and especially experts, demonstrate greater accuracy and speed in perceiving single poses, as evidenced by response times that are more consistent and less variable. In contrast, gymnasts exhibit better performance in object-based transformation tasks. These findings corroborate the results of Feng et al. (2017), which showed that sports experts could also make same-different judgements about cubes and hands.

Uttal et al.'s (2013a) taxonomy of spatial abilities is valuable in broadening the perspective that specific sports affect varied visuospatial abilities. The framework emphasizes the intrinsic and extrinsic dimensions of spatial abilities and static and dynamic visuospatial abilities. Extrinsic and dynamic visuospatial abilities are frequently observed in team sports

TABLE 2 Results of the 4 (group: SS-E, SS-N, GS-E, and GS-N) × 4 (angle: 80°, 160°, 240°, and 320°) ANOVA with repeated measures for response time and accuracy of the mental rotation task with poses, cubes, letters, and hands (mean & SD).

	SS-E (n = 17)	SS-N (n = 19)	GS-E (n = 10)	GS-N (n = 10)	angle	angle x sport	angle x expertise	angle x sports x expertise
Mental rotation with soccer-specific poses								
RT (ms)	3244 ± 1227	3440 ± 1360	2850 ± 770	3027 ± 1123	$F(1.91,99.2) = 33.9$, $p < 0.001$, $\eta^2p = 0.395$	$F(1.91,99.2) = 0.04$, $p = 0.957$, $\eta^2p = 0.007$	$F(1.91,99.2) = 0.78$, $p = 0.455$, $\eta^2p = 0.015$	$F(1.91,99.2) = 0.79$, $p = 0.785$, $\eta^2p = 0.004$
ACC (%)	77.0 ± 15.9	77.2 ± 17.0	88.5 ± 6.3	86.1 ± 13.3	$F(2.13,111) = 20.7$, $p < 0.001$, $\eta^2p = 0.285$	$F(2.13,111) = 0.35$, $p = 0.717$, $\eta^2p = 0.007$	$F(2.13,111) = 1.19$, $p = 0.311$, $\eta^2p = 0.022$	$F(2.13,111) = 0.17$, $p = 0.854$, $\eta^2p = 0.003$
Mental rotation task with cubes								
RT (ms)	3935 ± 2197	4172 ± 1817	3943 ± 1251	4780 ± 1511	$F(2.58,134) = 38.6$, $p < 0.001$, $\eta^2p = 0.426$	$F(2.58,134) = 2.12$, $p = 0.111$, $\eta^2p = 0.039$	$F(2.58,134) = 0.51$, $p = 0.646$, $\eta^2p = 0.010$	$F(2.58,134) = 2.06$, $p = 0.118$, $\eta^2p = 0.038$
ACC (%)	66.3 ± 14.0	61.6 ± 11.9	79.3 ± 9.1	79.0 ± 12.0	$F(2.58,134) = 18.9$, $p < 0.001$, $\eta^2p = 0.267$	$F(2.58,134) = 1.47$, $p = 0.230$, $\eta^2p = 0.027$	$F(2.58,134) = 0.84$, $p = 0.459$, $\eta^2p = 0.016$	$F(2.58,134) = 1.32$, $p = 0.273$, $\eta^2p = 0.025$
Mental rotation task with letters								
RT (ms)	1693 ± 525	1622 ± 482	1253 ± 315	1206 ± 335	$F(2.31,99.1) = 48.9$, $p < 0.001$, $\eta^2p = 0.532$	$F(2.31,99.1) = 3.59$, $p = 0.026$, $\eta^2p = 0.077$	$F(2.31,99.1) = 4.56$, $p = 0.009$, $\eta^2p = 0.096$	$F(2.31,99.1) = 1.35$, $p = 0.264$, $\eta^2p = 0.030$
ACC (%)	89.9 ± 10.5	93.3 ± 6.4	92.6 ± 6.7	94.0 ± 5.2	$F(2.03,86.1) = 12.4$, $p < 0.001$, $\eta^2p = 0.223$	$F(2.03,86.1) = 1.81$, $p = 0.170$, $\eta^2p = 0.040$	$F(2.03,86.1) = 1.67$, $p = 0.194$, $\eta^2p = 0.037$	$F(2.03,86.1) = 1.06$, $p = 0.352$, $\eta^2p = 0.024$
Mental rotation task with hands								
RT (ms)	2182 ± 707	1965 ± 665	1647 ± 602	1368 ± 290	$F(2.39,113) = 28.5$, $p < 0.001$, $\eta^2p = 0.378$	$F(2.39,113) = 1.44$, $p = 0.239$, $\eta^2p = 0.030$	$F(2.39,113) = 0.11$, $p = 0.926$, $\eta^2p = 0.002$	$F(2.39,113) = 1.04$, $p = 0.366$, $\eta^2p = 0.022$
ACC (%)	93.7 ± 4.0	88.7 ± 12.3	92.1 ± 8.1	95.7 ± 4.0	$F(3,141) = 4.86$, $p = 0.003$, $\eta^2p = 0.094$	$F(3,141) = 0.27$, $p = 0.846$, $\eta^2p = 0.006$	$F(3,141) = 0.76$, $p = 0.518$, $\eta^2p = 0.016$	$F(3,141) = 0.76$, $p = 0.521$, $\eta^2p = 0.016$

RT, response time; ACC, accuracy.

10.3389/fpsyg.2024.1355381

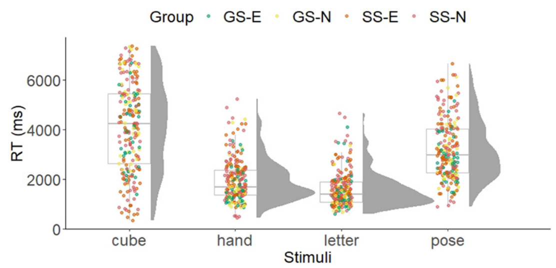


FIGURE 6
Results of response time in the mental rotation task separated by stimuli and groups. Boxplot with individual data points and density function. GS-E, gymnastic-specific expertise; SS-E, soccer-specific expertise; SS-N, soccer-specific novices.

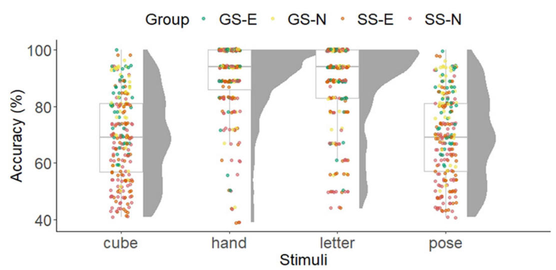


FIGURE 7
Results of accuracy in the mental rotation task separated by stimuli and groups. Boxplot with individual data points and density function. GS-E, gymnastic-specific expertise; SS-E, soccer-specific expertise; SS-N, soccer-specific novices.

like soccer (Matos and Godinho, 2006). Our exploratory and preliminary study found that soccer players demonstrate improved performance in perceptual tasks due to their better utilization of the visual field in peripheral vision and high binocular visual acuity. In contrast, sports such as gymnastics rely on intrinsic visuospatial abilities that depend on somatosensory information (Pietsch et al., 2019). Thus, this may explain why gymnasts excel in the object-based mental rotation task for all types of stimuli, including soccer-specific poses (see Pietsch, 2018).

4.1 Perceptual task with egocentric transformation

We propose that there was no object-based transformation in the initial perceptual task featuring soccer-specific poses. This is because the positive slope criterion of Cohen and Kubovy (1993) was not met. However, numerous studies demonstrate a linear or monotonic increase in reaction time associated with an angular disparity in tasks involving egocentric mental rotation, even though these studies often do not explore the theoretical differences between mental rotation, egocentric transformations, and perspective taking (Kessler and Rutherford, 2010; Jansen and Kaltner, 2014; Kaltner and Jansen, 2014; Voyer et al., 2017; Yu and Zacks, 2017). Based on these findings, it appears that relying solely on a linear correlation between increasing angular disparities and reaction times, as well as considering different instructions or tasks, is insufficient for distinguishing between object-based and egocentric transformations.

Thus, our study's results do not definitively rule out the possibility of object-based transformation. To successfully complete the mental rotation task in the back view, only a minimal rotation around the body's longitudinal axis is required to match the orientation of the target pose with one's own orientation. From the participants' perspective, mentally moving forward is enough to assume the presented soccer-specific target pose (Steggemann and Weigelt, 2011). While a frontal view of the poses at 80° and 320° angular deviation from the target figure may require an object-based transformation, the back view of the poses at 160° and 240° angular deviation from the target figure does not. The *post hoc* assessment of poses viewed frontally (at 80° and 320° angles) revealed a significantly faster response time (M = 1924, SD = 1172) than poses viewed from the back (M = 1673, SD = 787.6.4), $t(55) = 3.61$, $p < 0.01$, $d = 0.251$. These findings support Steggemann and Weigelt's (2011) explanation of an egocentric transformation.

Steggemann et al. (2011) demonstrated that athletes outperformed non-athletes only in mental left-right rotation tasks (egocentric transformations) when considering the effects of expertise and its advantages. Kaltner et al. (2014) demonstrated that sports expertise facilitated performance exclusively for egocentric transformations by eliciting embodied spatial transformations in response to the human body stimulus. However, no evidence of expertise influencing performance in an object-based transformation task with equal-unequal decisions was found. Furthermore, in Feng et al.'s (2017) study on egocentric transformation, participants' ability to judge body postures was expedited due to their greater familiarity with bodily experiences from a first-person perspective in everyday life. This familiarity potentially enhances performance on egocentric mental rotation tasks. Habacha et al. (2014) discovered a selective effect of motor expertise, as evidenced by the superior performance of sports experts. This was attributed to the increased embodiment of spatial transformations, as indicated by a higher correlation between the mental rotation task and the sports situation. The study affirms a strong association between physical movement and mental execution and identifies the particular aspects of physical activity that affect mental rotation performance. Jola and Mast (2005a,b) conducted tests on both elite dancers and nondancers using a mental body rotation task. They observed no discrepancies between the two groups in their egocentric task involving line drawings of human bodies.

Our exploratory and preliminary study observed No significant group differences in response times. As expected, GS-E and GS-N exhibited the longest response times. Regarding accuracy, a critical factor in decision-making and follow-up actions specific to sports such as soccer, SS-E demonstrated an advantage with an average accuracy rate of 87.7% (compared to GS-E's 80.8%, SS-E's 80.8%, and SS-N's 78.3%). However, the group differences in accuracy, similar to those observed for response times, did not reach significance. This variability in both response time and accuracy is evident in GS-E, GS-N, and SS-N. In contrast, SS-E presents less variance, suggesting a homogeneous group with consistent performance. Gymnasts exhibit lower accuracy rates due to difficulties in identifying soccer-specific poses, resulting in slower decision-making regarding which leg to use for kicking. Egocentric transformations pose a greater challenge for them. Soccer players use the poses to train three skills: full-span kick, cross ball, and inside kick, which are common movements in the game. These skills are observed and practiced during training routines.

4.2 Mental rotation task with object-based transformation

The significant associations between the response times of the cubes, hands, and poses indicate that the parity decision induced an object-based transformation. Specifically, we noted a pronounced linear trend in object-based mental rotation for unfamiliar cube figures. These findings align with Kosslyn et al.'s (1998) research, which exhibited a robust object-based transformation for cube figures. The cube figures elicit the longest response times compared to all other stimuli, with the lowest response accuracy. There is a significant difference in response accuracy between gymnasts and soccer players. It is reasonable to assume that sport-specific expertise affects accuracy. Gymnasts possess enhanced spatial ability, which aids in their object-based mental rotation skills, specifically for internally represented objects like cubes, due to the physical requirements of their sport.

Although there seem to be consistent results in mental rotation tasks involving objects such as cubes, findings for human figure rotation are not universally clear-cut and do not exhibit a linear relationship between angular disparity and response time. Parsons observed no linear correlation between response time and angular disparity. The initial research on the mental rotation of figures traces back to Parsons' 1987 study. He attributed these outcomes to participants' various techniques to complete the mental rotation tasks. Parsons argued that in contrast to comparing two cubes, mental body rotation necessitates participants to adopt the body position and orientation of the shown stimulus. The study by Zacks et al. (2002) indicates that two types of transformations can be produced depending on the task and instructions. The first type is object-based transformation, which involves mentally rotating objects relative to the reference frame of the environment. The second type is the egocentric, perspective-based transformation, which involves mentally rotating one's own point of view relative to the object's reference frame. Due to the linear relationship between angular disparity and response time, we can infer an object-based transformation for the poses analyzed in our research.

Due to the linear relationship between response time and angular disparity for the hand stimuli, it can be inferred that the processing of the task involves object-based mental rotation. Gymnasts outperformed both soccer groups in responding to all hand positions and orientations, which may be attributed to their sport-specific expertise and frequent use of hands. This outcome suggests that motor processes are utilized while performing this task. Response times cannot be assumed to be particularly long when encountering difficulty or inconvenience in positioning their hand to compare the target figure, as the 80° and 320° orientations vary significantly from the 160° orientation but not from the 240° orientation. These findings contrast with the studies conducted by Funk et al. (2005) and Petit and Harris (2005). Both groups of researchers demonstrated that response times were influenced by various factors, including the position of the participant's own hands, the comfort of the posture depicted, and the difficulty in moving one's hand into the position of the displayed hand. Additionally, the study revealed that the kinematic constraints of natural motion affect the direction of mental transformation and, therefore, response time trajectories. Response times were affected by both angular disparity and the feasibility of hand movements. This suggests that the body's motor system plays a role in the mental rotation process when dealing with hand stimuli, distinguishing it from other stimuli types.

In contrast, there is no evidence of mental rotation occurring with letters, as there is no significant positive linear trend between response time and angular disparity. Additionally, the linear increase observed in Cooper and Shepard's (1978) studies was not as distinct as that observed for cube figures. This finding supports the idea that the mental rotation of objects, like letters, is done using allocentric coordinates, while the mental rotation of body parts, like hands, is done using egocentric coordinates. Another possible explanation for the absence of a linear relationship is that participants may have a higher tolerance for slope when determining the equality of letters (Corballis, 1986). In this regard, the study by Young et al. (1980) demonstrated that neither children nor adults need to mentally rotate letters to identify misaligned letters, as the critical features for recognition are extracted. The visual system detects the objects' structural properties that remain unchanged despite angular variations. These angle-independent and orientation-independent features help identify the letters' corresponding components. Once determined, the parity decision can be made without mental rotation.

4.3 Limitation, implication, and future direction

It is essential to note the methodological limitations of our research. We could not compare all stimuli directly because cubes and poses are 3D images rotated around three axes, while letters and hands are two-dimensional and rotated on one axis only. As a result, we averaged mental rotation performance across all rotation axes in the respective stimuli instead of showing the function of a single rotation axis. When designing a mental rotation experiment, it is crucial to consider the variety of information processing steps involved and that response time does not reflect the pure "mental rotation time". Heil (2002) and Jansen-Osmann and Heil (2006) describe analogous sequential processing steps. The mental rotation tasks involve stimulus identification, mental rotation, parity decision, response selection, and motor processes. When discussing response time in mental rotation tasks, it is important to acknowledge that this term represents all processing steps involved. Future studies would benefit from differentiating and analyzing each step to enable detailed statements about the mental rotation process. For a general overview of test design (albeit in relation to psychometric tests and sex differences), see also (Jost and Jansen, 2023). The summarized literature includes comparisons of the stimulus material and the axis of rotation.

The sample size is too small to draw practical and reliable conclusions about the evaluated factors. According to Brysbaert (2019, p. 27), very little research can be adequately conducted with a sample of less than N = 100 participants per between-subject group. Brysbaert emphasizes that studies with inadequate sample sizes often fail to detect genuine effects. When effects are observed in such studies, it is usually due to disproportionately large effect sizes within the small samples. Additionally, there is a risk that results that appear to be significant may not actually hold, especially in complex research designs such as the one in the present study. Brysbaert suggests that research with limited participant numbers should focus on topics that can yield reliable results even with a limited amount of data rather than defending studies with too small sample sizes. Specifically, the focus should be on the main effects between two reliably measured within-subject conditions. In this respect, particular caution is required when interpreting the interaction effects within the scope of the study. Additionally, Brysbaert and Stevens (2018) suggest that 216 trials per condition is too low. The authors recommend at least 40 trials per condition to account for the natural variance in reaction times. However, our study only has nine trials per stimulus.

Furthermore, it would have been advantageous to more distinctly separate the groups of soccer-specific experts and novices. Swann et al. (2015) developed a classification system for sports expertise samples, categorizing various types of elite competitive athletes. They propose a method for selecting a valid expert sample. Our exploratory and preliminary study considers variables A, which refers to "highest standard of performance," and B, which signifies "success at the athlete's highest level," in its definition of sports comparison. It distinguishes between soccer players of higher and lower leagues and inquires about their highest sports success. However, the study does not consider variable C, which pertains to "experience at the athlete's highest level." Additionally, the variables for comparing sports (D: "Competitiveness of the sport in the athlete's country" and E: "Global competitiveness of the sport") were not considered, as all athletes were recruited in Germany.

The chosen soccer-specific poses should have been determined through a consensus of experts. While the current study recognizes a difference in response times between individual poses with egocentric transformation in soccer players versus gymnasts, selecting appropriate poses based on a prior survey would have been beneficial. More accurate results could have been achieved by choosing poses with the highest level of agreement (and recognition).

Specific training can lead to specialized adaptations and improved performance on spatial cognitive tasks. Individuals experiencing difficulties with mental rotation tasks may benefit from this type of training. Concurrently, cognitive training targeting spatial cognition may also improve sport-specific skills. Performance could be further augmented during training breaks or injury interruptions. The precise effects, relationships, and dependencies of these mechanisms are currently unknown, hindering our ability to provide clear recommendations for action.

5 Conclusion

In this exploratory and preliminary study, we investigated the mental rotation abilities of gymnasts and soccer players at different levels of expertise. It was found that soccer players, particularly those with high expertise, are faster at recognizing soccer-specific poses when making left-right decisions, indicating a mental rotation process with egocentric transformation. In contrast, our findings show that gymnasts can recognize soccer-specific poses rotated around various axes more quickly and with fewer errors. These results suggest that gymnasts perform faster and more accurately in mental rotation tasks involving object-based transformations, particularly with unknown cube figures, line drawings of hands, and soccer-specific poses. At the same time, no significant differences were observed in the mental rotation of letters. These results suggest that sporting practice and associated motor expertise may enhance the ability for mental rotation, particularly regarding egocentric transformations.

However, it is essential to acknowledge that the preliminary study has methodological constraints due to its small sample size and the limited number of trials per condition. Therefore, the lack of statistical significance in our results does not necessarily indicate the absence of an effect or a relationship between the variables studied. An actual effect may exist but could not be statistically proven due to insufficient sample size and test power. This affects the robustness of the findings and calls for further research with larger sample sizes and increased trials (see Brysbaert, 2019) in mental rotation experiments.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Commission on Responsibility in Research (Ethics Commission) of the University of Stuttgart. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin. Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article. All assessments were conducted in accordance with the ethical rules for research in human participants following the Declaration of Helsinki and its later amendments (World Medical and Association, 2015).

Author contributions

TK: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review and editing. NS: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

We thank the volunteers who participated in the study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2024.1355381/full#supplementary-material

References

Annett, M., and Annett, J. (1979). Individual differences in right and left reaction time. *Br. J. Psychol.* 70, 393–404.

Beilock, S. L. (2008). Beyond the playing field: sport psychology meets embodied cognition. *Int. Rev. Sport Exerc. Psychol.* 1, 19–30.

Ben Mahfoudh, H., and Zoudji, B. (2022). The role of visuospatial abilities and the level of expertise in memorising soccer animations. *Int. Rev. Sport Exerc. Psychol.* 20, 1033–1048.

Bhalla, M., and Proffitt, D. R. (1999). Visual–motor recalibration in geographical slant perception. *J. Exp. Psychol. Hum. Perception Performance* 25, 1076–1096. doi: 10.1037//0096-1523.25.4.1076

Blake, R., and Shiffrar, M. (2007). Perception of human motion. *Annu. Rev. Psychol.* 58, 47–73.

Bott, H., Poltz, N., and Ehlert, A. (2023). Assessment of mental rotation performance at primary school age. A computer-based test procedure for first to third grades (cMR). *Diagnostica* 69, 121–132. doi: 10.1026/0012-1924/a000309

Bruland, R. C., and van der Kamp, J. (2012). Are action-specific effects on perception action-specific? *Zeitschrift für Sportpsychologie* 19, 57–69.

Brysbaert, M. (2019). How many participants do we have to include in properly powered experiments? a tutorial of power analysis with reference tables. *J. Cogn.* 2:16. doi: 10.5334/joc.72

Brysbaert, M., and Stevens, M. (2018). Power analysis and effect size in mixed effects models: a tutorial. *J. Cogn.* 1:9.

Buckley, J., Seery, N., and Canty, D. (2018). A heuristic framework of spatial ability: a review and synthesis of spatial factor literature to support its translation into STEM education. *Educ. Psychol. Rev.* 30, 947–972.

Caldwell, A., and Lakens, D. (2019). *Power Analysis with Superpower. Self Published on GitHub*. Available Online at: https://aaroncaldwell.us/SuperpowerBook/ (accessed January 29, 2024).

Calvo-Merino, B., Glaser, D. E., Grèzes, J., Passingham, R. E., and Haggard, P. (2005). Action observation and acquired motor skills: an FMRI study with expert dancers. *Cereb. Cortex* 15, 1243–1249. doi: 10.1093/cercor/bhi007

Casile, A., and Giese, M. A. (2006). Nonvisual motor training influences biological motion perception. *Curr. Biol.* 16, 69–74. doi: 10.1016/j.cub.2005.10.071

Cavina-Pratesi, C., and Hesse, C. (2013). Why do the eyes prefer the index finger? simultaneous recording of eye and hand movements during precision grasping. *J. Vision* 13, 15. doi: 10.1167/13.5.15

Cohen, D., and Kubovy, M. (1993). Mental rotation, mental representation, and flat slopes. *Cogn. Psychol.* 25, 351–382. doi: 10.1006/cogp.1993.1009

Cohen, J. (1988). *Statistical Power Analysis for the Behavioural Sciences*, 2nd Edn. Mahwah: Erlbaum Associates.

Cooper, L. A. (1975). Mental rotation of random two-dimensional shapes. *Cogn. Psychol.* 7, 20–43. doi: 10.1016/s0278-2626(03)00077-0

Cooper, L. A., and Shepard, R. N. (1973). The time required to prepare for a rotated stimulus. *Mem. Cogn.* 1, 246–250.

Cooper, L. A., and Shepard, R. N. (1978). "Transformations on representations of objects in space," in *Perceptual Coding* (New York, NY: Academic Press), 105–146.

Corballis, M. C. (1986). Is mental rotation controlled or automatic? *Mem. Cogn.* 14, 124–128.

Dicks, M., Araújo, D., and van der Kamp, J. (2019). "Perception-action for the study of anticipation and decision making," in *Anticipation and Decision Making in Sport*, eds A. M. Williams and R. Jackson (Milton Park: Routledge), 181–199.

Eskenazi, T., Grosjean, M., Humphreys, G. W., and Knoblich, G. (2009). The role of motor simulation in action perception: a neuropsychological case study. *Psychol. Res.* 73, 477–485. doi: 10.1007/s00426-009-0231-5

Feng, T., Zhang, Z., Ji, Z., Jia, B., and Li, Y. (2017). Selective effects of sport expertise on the stages of mental rotation tasks with object-based and egocentric transformations. *Adv. Cogn. Psychol.* 13, 248–256. doi: 10.5709/acp-0225-x

Funk, M., Brugger, P., and Wilkening, F. (2005). Motor processes in children's imagery: the case of mental rotation of hands. *Dev. Sci.* 8, 402–408.

Ha, O., and Fang, N. (2016). Spatial ability in learning engineering mechanics: critical review. *J. Professional Issues Eng. Educ. Pract.* 142:04015014.

Habacha, H., Lejeune-Poutrain, L., Margas, N., and Molinaro, C. (2014). Effects of the axis of rotation and primordially solicited limb of high level athletes in a mental rotation task. *Hum. Movement Sci.* 37, 58–68. doi: 10.1016/j.humov.2014.06.002

Habacha, H., Mallek, M., Moreau, D., Khalfallah, S., and Mkaouer, B. (2022). Differences in mental rotation strategies depend on the level of motor expertise. *Am. J. Psychol.* 135, 325–336. doi: 10.1007/s00221-012-3324-0

Heil, M. (2002). The functional significance of ERP effects during mental rotation. *Psychophysiology* 39, 535–545.

Heinen, T. (2013). Does the athletes' body shape the athletes' mind? a few ideas on athletes' mental rotation performance. commentary on Jansen and Lehmann. *Adv. Cogn. Psychol.* 9, 99–101. doi: 10.2478/v10053-008-0136-7

Hohmann, T., Troje, N. F., Olmos, A., and Munzert, J. (2011). The influence of motor expertise and motor experience on action and actor recognition. *J. Cogn. Psychol.* 23, 403–415.

Holden, M. P., Newcombe, N. S., and Shipley, T. F. (2015). Categorical biases in spatial memory: the role of certainty. *J. Exp. Psychol. Learn. Mem. Cogn.* 41, 473–481. doi: 10.1037/a0038119

Jansen, P., and Kaltner, S. (2014). Object-based and egocentric mental rotation performance in older adults: the importance of gender differences and motor ability. *Aging Neuropsychol. Cogn.* 21, 296–316. doi: 10.1080/13825585.2013.805725

Jansen, P., and Lehmann, J. (2013). Mental rotation performance in soccer players and gymnasts in an object-based mental rotation task. *Adv. Cogn. Psychol.* 9, 92–98. doi: 10.2478/v10053-008-0135-8

Jansen-Osmann, P., and Heil, M. (2006). Violation of pure insertion during mental rotation is independent of stimulus type, task, and subjects' age. *Acta Psychol.* 122, 280–287. doi: 10.1016/j.actpsy.2005.12.006

Jola, C., and Mast, F. W. (2005a). "Dance images. mental imagery processes in dance," in *Dance and Cognition*, eds J. Birringer and J. Fenger (Münster: LIT), 211–232.

Jola, C., and Mast, F. W. (2005b). Mental object rotation and egocentric body transformation: two dissociable processes? *Spatial Cogn. Comput.* 5, 217–237. doi: 10.1007/s00221-017-5125-y

Jost, L., and Jansen, P. (2020). A novel approach to analyzing all trials in chronometric mental rotation and description of a flexible extended library of stimuli. *Spatial Cogn. Comput.* 20, 234–256.

Jost, L., and Jansen, P. (2023). The influence of the design of mental rotation trials on performance and possible differences between sexes: a theoretical review and experimental investigation. *Quarterly J. Exp. Psychol.* 77, 1250–1271. doi: 10.1177/17470218231200127

Kail, R., Pellegrino, J., and Carter, P. (1980). Developmental changes in mental rotation. *J. Exp. Child Psychol.* 29, 102–116.

Kaltner, S., and Jansen, P. (2014). Emotion and affect in mental imagery: do fear and anxiety manipulate mental rotation performance? *Front. Psychol.* 5:792. doi: 10.3389/fpsyg.2014.00792

Kaltner, S., Riecke, B. E., and Jansen, P. (2014). Embodied mental rotation: a special link between egocentric transformation and the bodily self. *Front. Psychol.* 5:505. doi: 10.3389/fpsyg.2014.00505

Kamruddin, E. (2022). The influence of the mental rotation task on mental rotation skills in badminton. *Psychology* 12, 890–893.

Kessler, K., and Rutherford, H. (2010). The two forms of visuo-spatial perspective taking are differently embodied and subserve different spatial prepositions. *Front. Psychol.* 1:213. doi: 10.3389/fpsyg.2010.00213

Kiefer, M., and Trumpp, N. M. (2012). Embodiment theory and education: the foundations of cognition in perception and action. *Trends Neurosci. Educ.* 1, 15–20. doi: 10.3389/fpsyg.2017.00556

Kosslyn, S. M., DiGirolamo, G. J., Thompson, W. L., and Alpert, N. M. (1998). Mental rotation of objects versus hands: neural mechanisms revealed by positron emission tomography. *Psychophysiology* 35, 151–161.

Krúger, M., and Krist, H. (2009). Imagery and motor processes—When are they connected? The mental rotation of body parts in development. *J. Cogn. Dev.* 10, 239–261. doi: 10.1080/15248370903389341

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Front. Psychol.* 4:863. doi: 10.3389/fpsyg.2013.00863

Lameira, A. P., Guimarães-Silva, S., Werneck-Galvão, C., Pereira Junior, A., and Gawryszewski, L. G. (2008). Recognition of hand shape drawings on vertical and horizontal display. *Psychol. Neurosci.* 1, 35–40.

Linn, M. C., and Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: a meta-analysis. *Child Dev.* 56, 1479–1498.

Mann, D. T. Y., Williams, A. M., Ward, P., and Janelle, C. M. (2007). Perceptual-cognitive expertise in sport: a meta-analysis. *J. Sport Exerc. Psychol.* 29, 457–478. doi: 10.1123/jsep.29.4.457

Markman, A. B., and Brendl, C. M. (2005). Constraining theories of embodied cognition. *Psychol. Sci.* 16, 6–10.

Matos, R. M. N., and Godinho, M. A. B. (2006). "Influence of sports practice in the useful field of vision in a simulated driving test," in *AIESEP 2005 World Congress-"Active Lifestyles: the Impact of Education and Sport"*, (Portugal: Faculdade de Motricidade Humana), 557–566.

Moreau, D. (2012). The role of motor processes in three-dimensional mental rotation: shaping cognitive processing via sensorimotor experience. *Learn. Indiv. Diff.* 22, 354–359. doi: 10.1016/j.lindif.2012.02.003

Moreau, D., Clerc, J., Mansy-Dannay, A., and Guerrien, A. (2012). Enhancing spatial ability through sport practice. *J. Individ. Dif.* 33, 83–88.

Moreau, D., Mansy-Dannay, A., Clerc, J., and Guerrién, A. (2011). Spatial ability and motor performance: assessing mental rotation processes in elite and novice athletes. *Int. J. Sport Psychol.* 42, 525–547.

O'Regan, J. K., and Noë, A. (2001). A sensorimotor account of vision and visual consciousness. *Behav. Brain Sci.* 24, 939–973. doi: 10.1017/s0140525x01000115

Parsons, L. M. (1987). Imagined spatial transformation of one's body. *J. Exp. Psychol. General* 116, 172–191.

Peters, M., and Battista, C. (2008). Applications of mental rotation figures of the Shepard and Metzler type and description of a mental rotation stimulus library. *Brain Cogn.* 66, 260–264. doi: 10.1016/j.bandc.2007.09.003

Petit, L., and Harris, I. (2005). Anatomical limitations in mental transformations of body parts. *Vis. Cogn.* 12, 737–758.

Pietsch, S. (2018). The different point of view–a visual-spatial taxonomy for sports. *J. Athletic Enhancement* 7:7.

Pietsch, S., Jansen, P., and Lehmann, J. (2019). The choice of sports affects mental rotation performance in adolescents. *Front. Neurosci.* 13:224. doi: 10.3389/fnins.2019.00224

Pizzera, A., and Raab, M. (2012). Perceptual judgments of sports officials are influenced by their motor and visual experience. *J. Appl. Sport Psychol.* 24, 59–72.

Proffitt, D. R. (2006). Embodied perception and the economy of action. *Perspect. Psychol. Sci.* 1, 110–122.

Proffitt, D. R., Bhalla, M., Gossweiler, R., and Midgett, J. (1995). Perceiving geographical slant. *Psychon. Bull. Rev.* 2, 409–428.

R Core Team (2023). *R: a Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing.

Schmidt, M., Egger, F., Kieliger, M., Rubeli, B., and Schüler, J. (2016). Gymnasts and orienteers display better mental rotation performance than nonathletes. *J. Individ. Dif.* 37, 1–7.

Shepard, R. N., and Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science* 171, 701–703.

Shiffrar, M., and Heinen, T. (2011). Athletic ability changes action perception: embodiment in the visual perception of human movement. *Z. Sportpsychol.* 17, 1–13.

Shiffrar, M., and Heinen, T. (2015). Die Fähigkeiten von Athleten verändern deren Wahrnehmung von Handlungen. Zeitschrift für Sportpsychologie. Göttingen: Hogrefe.

Sorby, S. A., Vieau, S., and Yoon, S. Y. (2021). "The relationship between spatial skills and solving problems in engineering mechanics," in *Proceedings of the 2021 ASEE Virtual Annual Conference Content Access*, (Piscataway, NJ: IEEE). doi: 10.3390/brainsci12060736

Sparrow, W. A., and Sherman, C. (2001). Visual expertise in the perception of action. *Exerc. Sport Sci. Rev.* 29, 124–128.

Steggemann, Y., Engbert, K., and Weigelt, M. (2011). Selective effects of motor expertise in mental body rotation tasks: comparing object-based and perspective transformations. *Brain Cogn.* 76, 97–105. doi: 10.1016/j.bandc.2011.02.013

Steggemann, Y., and Weigelt, M. (2011). Der kopf turnt saltos.! selektive effekte sportlicher bewegungserfahrung auf die mentale rotationsleistungvon menschlichen figuren. *Zeitschrift für Sportpsychologie* 18, 133–140.

Stuhr, C., Hughes, C. M., and Stöckel, T. (2020). The role of executive functions for motor performance in preschool children as compared to young adults. *Front. Psychol.* 11:542282. doi: 10.3389/fpsyg.2020.01552

Swann, C., Moran, A., and Piggott, D. (2015). Defining elite athletes: issues in the study of expert performance in sport psychology. *Psychol. Sport Exerc.* 16, 3–14.

Takano, Y. (1989). Perception of rotated forms: a theory of information types. *Cogn. Psychol.* 21, 1–59.

Tomasino, B., Maieron, M., Guatto, E., Fabbro, F., and Rumiati, R. I. (2013). How are the motor system activity and functional connectivity between the cognitive and sensorimotor systems modulated by athletic expertise? *Brain Res.* 1540, 21–41. doi: 10.1016/j.brainres.2013.09.048

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., et al. (2013a). The malleability of spatial skills: a meta-analysis of training studies. *Psychol. Bull.* 139, 352–402.

Uttal, D. H., Miller, D. I., and Newcombe, N. S. (2013b). Exploring and enhancing spatial thinking: links to achievement in science, technology, engineering, and mathematics? *Curr. Dir. Psychol. Sci.* 22, 367–373.

Voss, M. W., Kramer, A. F., Basak, C., Prakash, R. S., and Roberts, B. (2010). Are expert athletes 'expert'in the cognitive laboratory? a meta-analytic review of cognition and sport expertise. *Appl. Cogn. Psychol.* 24, 812–826.

Voyer, D., and Jansen, P. (2017). Motor expertise and performance in spatial tasks: a meta-analysis. *Hum. Movement Sci.* 54, 110–124. doi: 10.1016/j.humov.2017.04.004

Voyer, D., Jansen, P., and Kaltner, S. (2017). Mental rotation with egocentric and object-based transformations. *Quart. J. Exp. Psychol.* 70, 2319–2330.

Weigelt, M., and Memmert, D. (2021). The mental rotation ability of expert basketball players: identifying on-court plays. *Res. Quart. Exerc. Sport* 92, 137–145. doi: 10.1080/02701367.2020.1713289

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. New York, NY: Springer-Verlag.

Witt, J. K. (2011). Action's effect on perception. *Curr. Dir. Psychol. Sci.* 20, 201–206.

Witt, J. K., and Proffitt, D. R. (2008). Action-specific influences on distance perception: a role for motor simulation. *J. Exp. Psychol. Hum. Percept. Performance* 34, 1479–1492. doi: 10.1037/a0010781

Wohlschläger, A., and Wohlschläger, A. (1998). Mental and manual rotation. *J. Exp. Psychol. Hum. Percept. Performance* 24, 397–412.

World Medical and Association (2015). *Declaration of Helsinki. Ethical Principles for Medical Research involving Human Subjects. (64th WMA General Assembly)*. Fortaleza: World Medical Association.

Yang, Y., Wang, R., and Jia, X. (2003). Principal component analysis of motion patterns for the point-touch movement of the index finger. *J. Tsinghua Univer.* 43, 1476–1479.

Young, J. M., Palef, S. R., and Logan, G. D. (1980). The role of mental rotation in letter processing by children and adults. *Can. J. Psychol.* 34, 265–269.

Yu, A. B., and Zacks, J. M. (2017). Transformations and representations supporting spatial perspective taking. *Spatial Cogn. Comput.* 17, 304–337.

Zacks, J. M., Ollinger, J. M., Sheridan, M. A., and Tversky, B. (2002). A parametric study of mental spatial transformations of bodies. *Neuroimage* 16, 857–872. doi: 10.1006/nimg.2002.1129

frontiers | Frontiers in Psychology

TYPE Brief Research Report
PUBLISHED 06 June 2024
DOI 10.3389/fpsyg.2024.1356160

Check for updates

OPEN ACCESS

EDITED BY
Sean Müller,
Federation University Australia, Australia

REVIEWED BY
Khaya Morris-Binelli,
University of Notre Dame Australia, Australia
John Brenton,
Accelerated Skill Acquisition, Australia

*CORRESPONDENCE
Kylie A. Steel
k.steel@westernsydney.edu.au

RECEIVED 15 December 2023
ACCEPTED 07 May 2024
PUBLISHED 06 June 2024

CITATION
Kassem L, Pang B, Dogramaci S, MacMahon C, Quinn J and Steel KA (2024) Visual search strategies and game knowledge in junior Australian rules football players: testing potential in talent identification and development.
Front. Psychol. 15:1356160.
doi: 10.3389/fpsyg.2024.1356160

Visual search strategies and game knowledge in junior Australian rules football players: testing potential in talent identification and development

Lael Kassem[1], Bonnie Pang[2], Sera Dogramaci[1], Clare MacMahon[3], John Quinn[4,5] and Kylie A. Steel[1,6]*

[1]School of Health Sciences, Western Sydney University, Sydney, NSW, Australia, [2]Department for Health, University of Bath, Bath, United Kingdom, [3]Sport, Performance, and Nutrition Research Group, Latrobe University, Melbourne, VIC, Australia, [4]Greater Western Sydney Giants AFL, Sydney, NSW, Australia, [5]Quinn Elite Sport Services, Sydney, NSW, Australia, [6]The MARCS Institute for Brain, Behaviour and Development, Sydney, NSW, Australia

This study explored video-based decision-making and eye-movement behavior as a complementary method to assess the decision-making skills and knowledge of elite junior Australian Rules (AR) Football players. Performance was measured twice over an 18-month period. This approach tested a practical and reliable assessment of decision-making and game knowledge that does not contribute to physical training load. $N = 59$ participants were categorized based on their training age groups, U14 ($N = 38$, M_{age}13.37 ± 0.47) and U16 ($N = 21$, M_{age}14.80 ± 0.39). Participants watched 14 brief video clips and provided action choices while wearing eye-movement recording glasses that captured visual search patterns (e.g., fixations). Decision accuracy and speed of decision-making were also recorded. Participants with accurate decisions made significantly faster decisions compared to less skilled players ($p < 0.001$). Further, skilled participants had significantly fewer fixations of shorter duration compared to less skilled participants at both the initial and follow-up testing sessions ($p < 0.0001$). This suggests that eye-movement characteristics, remain a relatively stable measure over moderate periods of time. With the ability to differentiate between more and less skilled decision-makers, this proof-of-concept study proposes that examining eye movements in relation to decision-making and game knowledge is a viable tool for Talent Identification and Development (TID) to complement current measures. We provide a platform for further development and research in the quest for efficient and effective talent identification processes.

KEYWORDS

talent identification and development, Australian rules football, eye-movement behavior, decision-making, sport expertise

Introduction

The ability to identify performers with a high potential for development within junior team sports is challenging as it requires the consideration of a range of multidimensional elements (Falk et al., 2004; Farrow and Raab, 2008). These elements include physiological, physical, psychological, technical, and tactical variables (Light and Harvey, 2019). Another challenge in talent identification and development (TID) programs is forecasting elite performance over the course of a junior athlete's development into adult competition, given the influence of variable rates of maturation, individual learning and coaching styles, and the volume of and opportunity for practice. These challenges drive continued efforts to evolve TID systems to ensure that a club's resources are invested for the most suitable athletes.

The Australian Football League (AFL), which operates the Australian Rules (AR) football competition, uses a cross-sectional design to identify talented junior athletes with potential. A cross sectional approach assumes that identified sport-specific characteristics develop in a "linear" manner from elite junior to elite senior contexts (Güllich and Emrich, 2012) and tests athletes within the same age groups across a range of sport-specific performance measures. Talent-identified junior athletes are then invited to participate in development programs provided by regional and state-based academies. During these development programs, athletes are exposed to expert coaching and specific interventions designed to accelerate the acquisition of sport-specific skills required for success in elite senior competitions (Matthys, 2012; Johnston et al., 2018). The talent development program also exposes athletes to a greater volume of effortful, work-like practice and structured training, which some research shows facilitate elite performance (Ericsson et al., 1993; Ford et al., 2009). However, state-based academies can only take in a limited number of athletes who demonstrate the potential to achieve elite levels of performance. Hence with limited places in these programs, it is critical that the TID process is effective and efficient in its selections while also minimizing talent wastage.

Despite the necessity for efficiency in TID procedures, some limitations remain. First, athlete testing remains focused on the physical and physiological attributes of the individuals (e.g., speed and technical ability) (Burgess et al., 2012; Woods et al., 2016). Current practice also does not sufficiently consider the influence of variation in maturation status, and that chronological age and biological maturity do not develop at the same rate for all individuals. For example, a 15-year-old athlete may have a biological maturation above or below their actual age, which could influence performance characteristics (Beunen et al., 2000; Cripps et al., 2017; Gogos et al., 2020). Moreover, the relative age effect, in which birthdate relative to selection year for sport influences progression (Kelly et al., 2024), may amplify or moderate variations in maturation status. In addition, given the dynamic nature of sports, athletes tend to compensate for different strengths and weaknesses. For example, skilled decision-makers may use this ability to compensate for any physical and/or technical skill deficiencies (Wolstencroft and House, 2002; Woods et al., 2016).

A further limitation of current TID practices in AR football relates to how perceptual cognitive skills such as decision-making are assessed. Specifically, making fast and accurate decisions is a critical skill in AR football (Farrow et al., 2008; Woods et al., 2016), and requires a player to accurately select the correct choice from a range of alternatives under varied environmental contexts (Bruce et al., 2012; Dicks et al., 2019). Effective sport decision making also requires the integration of perceptual, cognitive, and motor skills (Gréhaigne et al., 2001), and in team sports, the ability to learn the team's particular game play and decision-making style as directed by the coach. This latter declarative knowledge is influential at junior stages of development and sport pedagogy (Dong et al., 2023).

Assessment of the tactical decision-making and declarative knowledge component of gameplay remains subjective. Indeed, the primary means of assessing decision-making is for recruiters to observe the performance of players in gameplay and pass judgment (Burgess et al., 2012; Larkin et al., 2020). While a primarily subjective process has its place (MacMahon et al., 2019), more objective assessments of perpetual-cognitive skills such as decision-making can complement subjective assessments and increase efficiency in TID efforts. In addition, junior athletes continue to develop declarative game knowledge, as an essential foundation for effective skill and tactical learning within professional contexts, and for general perceptual-cognitive skill (Américo et al., 2017). It is the challenge of assessing junior athletes' game knowledge and decision making through a more objective measure which this research aims to address.

To help understand the assessment of decision making and game knowledge, it is useful to dissect the underpinning processes. Decision-making is influenced by the ability to perceive and integrate complex moving patterns while allocating attentional resources to different key areas of dynamic plays, to make appropriate action choices (Williams and Jackson, 2019). Research has shown that three main factors underpin perceptual-cognitive skill, including visual search strategy, processing cognitive information, and anticipatory expectations within the display (Farrow et al., 2008; Woods et al., 2016). Visual search is most relevant to this study and may be measured relative to decision-making and game knowledge to improve TID programs. For example, research shows that skilled decision-makers use more efficient visual search strategies, and faster cognitive processing is linked to advanced cue utilization (Cardoso et al., 2021). These processes allow the identification of familiar patterns and key areas of importance within a display, enhancing anticipation (Allard and Starkes, 1980; Abernethy, 1990; Güllich and Emrich, 2006; Afonso et al., 2014; Williams and Jackson, 2019; Vater et al., 2020).

While several studies have attempted to quantify decision-making skill within AR football (Lorains et al., 2013; Woods et al., 2016), few have investigated the decision-making skills of junior athletes and the possible influence of maturation stages on this skill.

This study expands on previous findings, by using a film-based decision-making task and eye movement registration to explore the decision-making abilities and processes of elite junior AR football players. Specifically, this study explores the relationship between eye movement behavior and decision-making when differentiating more and less skilled junior decision-makers. Laurent et al. (2006) state skilled athletes exhibit fewer fixations and are more likely to identify and recognize more meaningful patterns in various scenarios more accurately when compared to less skilled players. Therefore, we hypothesized that skilled decision-makers would demonstrate more efficient eye-movement behaviors incorporating fewer fixations on redundant information, and more fixations of shorter duration on relevant cues when compared to less skilled decision-makers (Brams et al., 2019; Vitor de Assis et al., 2020).

Methods

Participants

Fifty-nine junior male AR football players were recruited for this study from an elite state football academy. At the time of testing no female squad had been established thus we were restricted to male players only. Players were members of the development squad for the 2018 season. Participants were categorized based on their training age groups, U14 (under 14 years) ($n = 38$, M_{age}13.37 ± 0.47) and U16 (under 16 years) ($n = 21$, M_{age}14.80 ± 0.39). Eighteen months later at the follow-up stage, only 18 of the original 59 participants were still members of the academy programs due to dropout or deselection. This second subsample provided an assessment of a relatively more successful subgroup. At the follow-up, participants were categorized in the same manner as the initial testing, that is respective to age U16 ($n = 13$, M_{age}14.91 ± 0.48) and U18 ($n = 5$, M_{age}16.40 ± 0.19). All participants provided informed consent before involvement with the study following the ethics protocol approved by the University Human Research Ethics Committee.

Video footage

The video footage for testing was provided by the professional AR football club involved in this study and was from stored game-day footage captured during the 2017 and 2018 seasons. Two different viewing perspectives were available: behind the goals and broadcast (televised footage). This ensured that all clips portrayed an offensive play. Players had between three and five options to choose from, with a lead time of 15 s before the decision-making moment (Woods et al., 2016). The initial videos were sourced from the 2017 season, while the follow-up group had a new set of videos sourced from the 2018 season.

Decision-making options

A total of 40 videos were identified for use in this study and reviewed by three highly experienced coaches, each with a minimum of 10 years of coaching at state or higher levels. Each coach was asked to identify the best passing options for the player in possession of the ball. Coaches independently ranked their top three options based on a 3–2–1–0 scale. Three represented the most "ideal" option and one represented the "least ideal," but still acceptable option. Zero points were awarded for any other "unacceptable" option. Only videos where all three coaches agreed upon the three options were included. The same coaches reviewed both initial and follow up video clips. From the range of clips provided to the coaches, 14 videos fitted the criteria to use in the initial testing, while a second set of videos fitting the same criteria were used in the follow up study.

Eye-tracking technology

TobiiPro Glasses 2 (Tobii AB, Stockholm, Sweden) eye-tracking glasses were used to measure the eye-movement behavior of the participants during the film-based decision-making task. The glasses collected visual search data at a rate of 50 Hz with 82° horizontal and 52° vertical visual angle of precision. The Tobii Pro Analyzer software program coded all recordings, which produced data for the following variables:

- Decision Time (DT): measured from the moment the video paused at the critical decision-making moment until the participant made a verbal response.
- Number of fixation(s): from the critical decision-making moment until participants made the first verbalization indicating their decision.
- Duration of fixation(s): Each coded fixation automatically also recorded the duration of fixation (across all locations).
- Total duration: the sum of all individual fixation durations.

In addition, the visual display was allocated into one of four areas: Defenders (D), Options (O), Player with the ball (B), and Space (S) for further analysis into participants' gaze behaviors.

Procedures

Testing was conducted across both regional and rural training locations which are within the geographical catchment area for the professional football club involved in this study. On arrival, the chief investigator read a dialogue sheet providing the details of the procedure. With consent, participants were fitted with eye-tracking glasses, followed by individual calibration. Participants stood in front of the screen, ensuring optimal positioning. If required, the height and distance measurements were adapted to each participant, ensuring eyesight was in the center of the display, allowing for the greatest compatibility.

Before the commencement of the task participants were told they would watch 14 individual clips of game day footage. At a critical point in play, the video clip would stop at which point participants were instructed to state what decision they would make if they were the player in possession of the ball. They were also told that they would only have a four-second window to verbalize (Woods et al., 2016). To ensure participants understood the process they watched two familiarization clips recorded from a similar viewpoint as the test clips. Once ready, participants viewed each of the 14 randomly sequenced clips providing their decision after each clip. The participant's score was matched with the scale (3–2–1–0) agreed upon by the three independent coaches. Participants received a 0 if they selected an option outside of the coach's identified appropriate options or if they did not make decisions within the allocated 4 s. An example of the final critical moment of a video clip is shown in Figure 1.

Statistical analysis

All results were collated, and various statistical procedures were implemented using the Statistical Package for Social Sciences (SPSS, Version 22). Descriptive statistics for all variables were calculated and are reported as mean ± standard deviation (SD). An alpha level of $p < 0.05$ was selected as the criterion for significance for all statistical procedures. A mixed model binomial logistic regression was used to account for the multiple responses, allowing the variance between videos to predict whether players can be correctly classified (skilled v. less skilled) from the independent variables.

Participants were initially divided into age groups of U14 ($n = 38$) or U16 ($n = 21$), based on a biannual age group system used within state academies for the initial testing phase. At the follow-up however, data were grouped as one age cohort, due to the small numbers and close ages ($n = 13$ for U16; $n = 5$ for U18). While this drop in participant numbers created a limitation to the data, the elite nature of the sample which naturally decreases as you reach the elite level of competition warrants continued analysis. Response accuracy (RA) was then used to stratify participants based on their decision-making. We categorized responses into two groups to allow for comparison and to predict the probability of observations falling into the skilled group (3 = Skilled; 2, 1, 0 = Less Skilled). To examine the potential of eye-movement data to predict skill level, a Receiver Operator Characteristic (ROC) curve was used to indicate the players' level of ability and to predict skilled decision-makers.

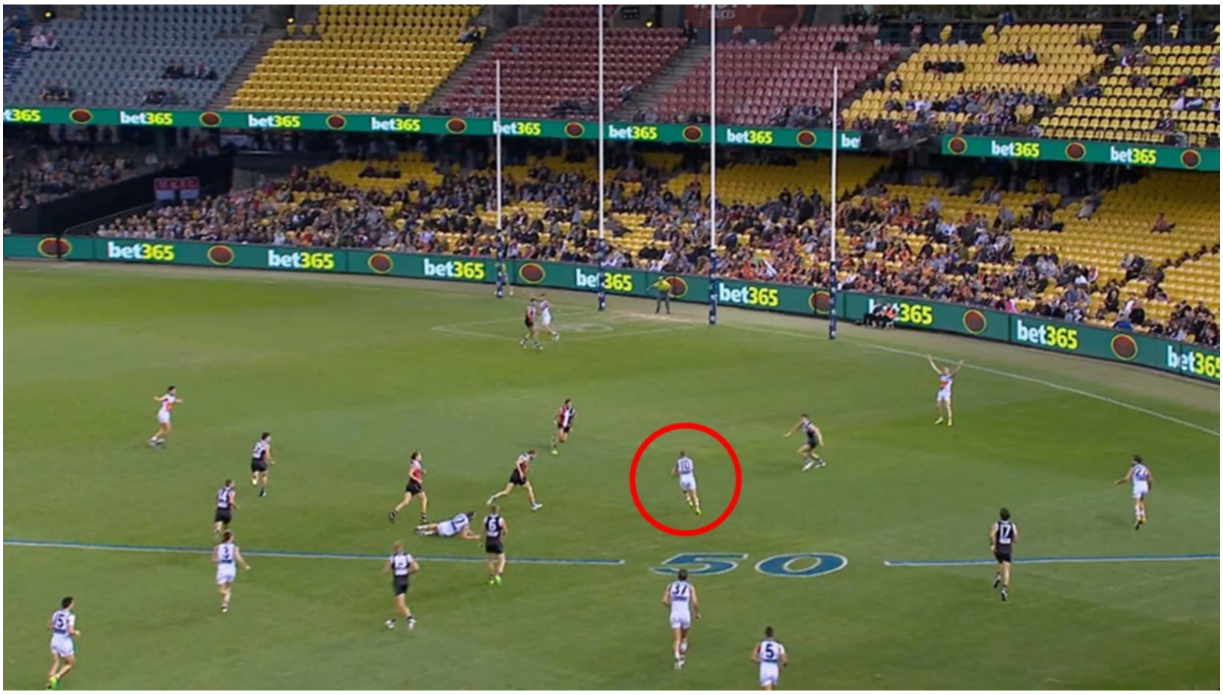


FIGURE 1
An example of a critical decision-making moment, used for the film-based task. For this example, the player with the ball is circled for reference. The team in dark the colored uniforms is the offensive team.

Two researchers independently coded the eye movement data via Tobii Pro Analyzer, which involved manually mapping fixation points and allocation of the different areas of interest (AOIs). Once coding was complete, the data was checked for consistency and agreement in coding locations and categories. The level of agreement between coders was very high (>95%). Where differences in coding occurred, the raters discussed and clarified the code.

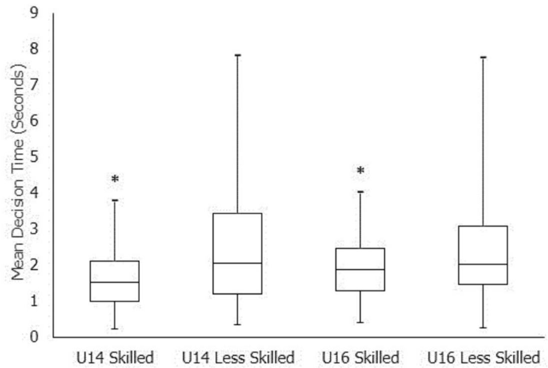


FIGURE 2
Mean decision time(s) and standard deviation between skilled and less skilled participants across both age groups. *Significantly different compared to the less skilled group ($p < 0.05$). Mid-line represents the median time for that group. Also note that the less skilled groups in each age range exhibited the greatest variation in decision time.

Results

Decision time

Initial test session group analysis

On average, the skilled participants within both U14 and U16 groups made significantly faster decisions (U14: 1.67 ± 0.87 vs. 2.58 ± 1.87; U16: 1.94 ± 0.84 vs. 2.46 ± 1.57) (Figure 2). A binomial logistical regression analysis indicated that for every 1 s increase in DT, there is 0.640 reduced likelihood of being in the skilled group ($p = 0.001$, 95%CI [0.3.02, 0.507]). The model also highlighted between age-group differences, with the older group more likely to be faster when making skilled decisions ($p = 0.023$, 95%CI [0.486, 0.947]).

Follow-up test session analysis

At the follow-up testing session, participants demonstrated a similar pattern to that in the initial test, where skilled participants made decisions significantly faster ($p < 0.05$) compared to less skilled participants (2.06 ± 0.80s vs. 3.84 ± 2.16 s, respectively) (Figure 3). The mixed model logistic regression indicated that for every 1-s increase in decision time, the likelihood of being in the skilled group reduced by 0.48[CI 95% 0.370, 0.624]. When compared to the initial test session group, overall, the follow-up test session participants made slower decisions compared to the initial responses (2.84 ± 1.78 s vs. 1.82 ± 1.17 s, respectively). However, this time difference was not significant and did not result in a more skilled response accuracy.

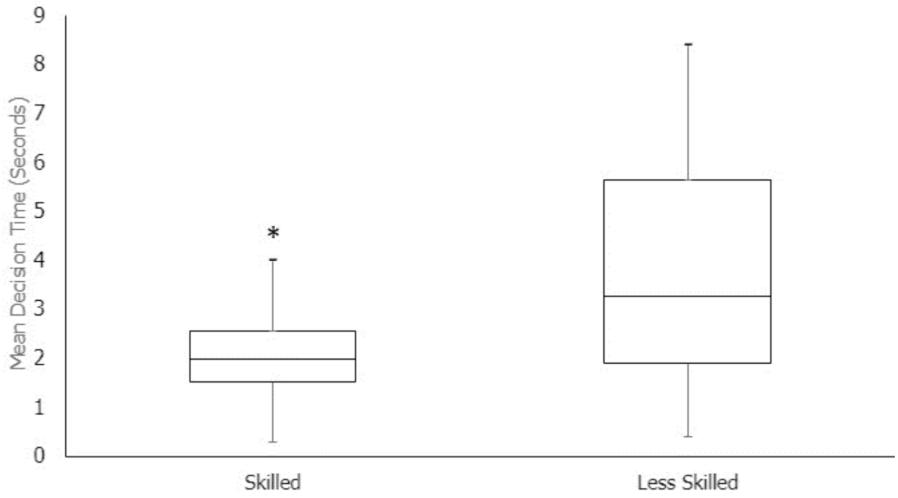


FIGURE 3
Mean decision time (seconds) between overall skilled and less skilled participants across all follow-up participants. *Significantly different from the less skilled group ($p < 0.05$). Mid-line represents the median time for that group.

Eye-movement behavior—initial test session participants

Number and duration of fixations

Visual search strategy (number of fixations and total fixation duration) was significantly different between skilled and less skilled groups as shown in Table 1. Specifically, the skilled groups had fewer fixations, and shorter fixation durations than the less skilled groups, in both age groups.

As Table 1 shows, a binomial logistical regression revealed that for every increase in fixation, participants reduced their likelihood of being in the skilled group by 0.863 95%CI [0.804, 0.927] ($p = 0.0001$). Further, the U16 group were more likely to make skilled decisions ($p = 0.0195$%CI [0.467, 0.903]) compared to the U14 group.

Moreover, a binomial logistic regression revealed that for every 1 s increase in duration, the participants reduced the likelihood of being in the skilled by 0.839 95%CI [0.735, 0.956] $p = 0.008$. Analysis also revealed the U16 cohort were more likely to make skilled decisions, $p = 0.018$ 95%CI [0.487, 0.934].

Fixations across AOIs

Skilled participants displayed significantly greater fixations on viable options (Figure 4). A binomial logistic regression revealed that each increase in fixation rate/time per decision option correlated with being a member of the skilled group by 0.829 95%CI [0.743, 0.924] ($p = 0.001$).

Eye-movement behavior—follow-up test session participants

The binomial logistic regression indicated that the number of fixations participants made, and the total duration of fixations were significantly different between initial and follow-up testing (Table 2).

TABLE 1 Mean number and total duration of fixations between skilled and less skilled groups across both age groups.

	Number of fixations (n) Mean ± SD		Fixation duration (s) Mean ± SD	
	U14	U16	U14	U16
Skilled	3.27 ± 1.99*	3.96 ± 2.34*	1.79 ± 1.14*	2.11 ± 1.26*
Less skilled	4.17 ± 2.56	4.46 ± 2.31	2.16 ± 1.37	2.29 ± 1.46

*Significantly different from the less skilled group ($p < 0.05$).

ROC curve analysis

An ROC curve was used to test the ability of the combined decision and eye movement measures to classify the skill level of the participants. At the initial testing time point when using the number of fixations, total duration of fixations, and decision time, the area under the ROC curve (AUC) was 0.80, 95%CI [0.770, 0.829]. While at the follow-up when accounting for the number of fixations, total duration of fixation and decision time, the area under the ROC curve was 0.803 95%CI [0.744, 0.862], which highlights an excellent level of discrimination (Figure 5). An AUC between 0.8 and 0.9 is considered excellent discriminability (Mandrekar, 2010).

Discussion

Traditional TID practices in AR football do not comprehensively assess the tactical, decision-making component required to succeed in elite sporting competitions, instead focusing on the more accessible physical performance measures (Woods et al., 2015). Nor do TID practices consider the influence of maturation stages. Therefore, the purpose of this study was to test a method to examine the decision-making skills and knowledge of junior AR football players using

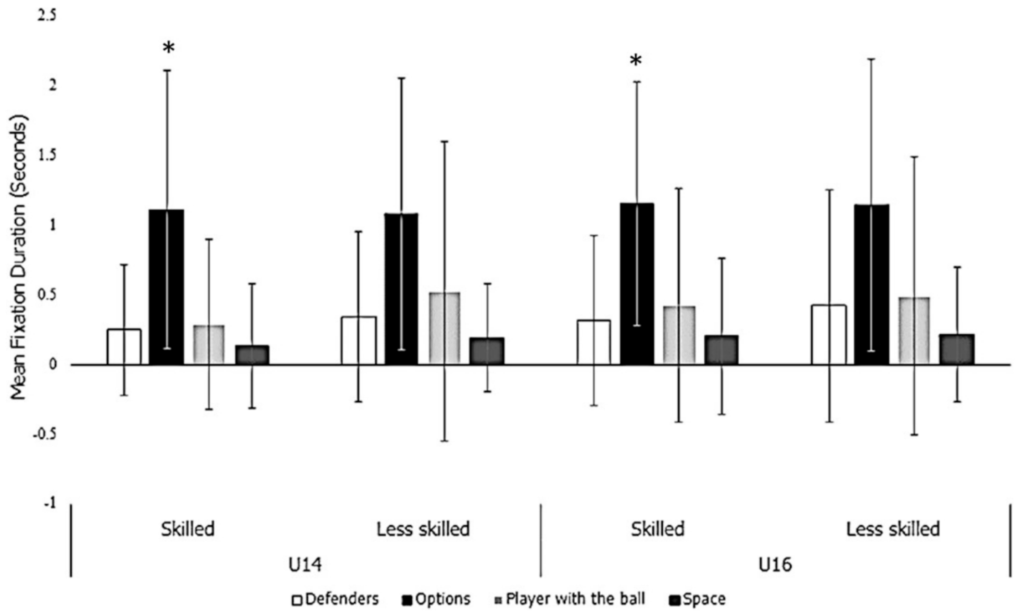


FIGURE 4
Average fixation duration (seconds) across fixation locations between skilled and age groups. *Significantly different from the less skilled group ($p < 0.05$).

TABLE 2 Mean duration of fixations between skilled and less skilled groups from initial to follow up testing.

	Number of fixations Mean ± SD		Mean duration of fixations Mean ± SD	
Group	Initial	Follow-up	Initial	Follow-up
Skilled	3.35 ± 2.09	4.22 ± 2.14*	1.91 ± 1.23	2.10 ± 1.08*
Less skilled	3.71 ± 2.41	6.10 ± 2.67*	2.04 ± 1.53	2.34 ± 0.99*

*Significantly different to pre-test ($p < 0.05$).

video-based testing and eye movement recording. A within-task skill level classification across two age groups (U14 and U16) was used. A secondary purpose was to examine the stability of decision-making skills and eye movement behavior across an 18-month period by re-testing.

A within-task criterion was used to stratify participants into skilled and less skilled groups based on their decisions and matched against the rankings of a panel of expert coaches. As hypothesized, skilled participants made significantly faster decisions regardless of age (U14/U16, $p = 0.001$). Further, the U16 cohort had significantly faster decision times and were more likely to make skilled decisions compared to the younger cohort (U14). Faster decision times were also evident for the skilled participants during the follow-up testing; however, it should be noted that faster decision-making times were not evident when comparing post (follow-up measurements) to the pre (initial) testing, which may be due to a smaller sample size.

Skilled decision-makers had significantly fewer fixations and shorter total fixation durations, which may be key indicators for the prediction of future skilled decision-making ability or knowledge. Fewer fixations have been associated with more skilled athletes in previous research and shows that skilled athletes are faster and more accurate at identifying and recognizing meaningful patterns in various scenarios while also excluding redundant cues (Laurent et al., 2006; Williams et al., 2011). Moreover, research has highlighted that skilled players are able to recognize and recall structured patterns of play more often (Williams and Ward, 2007), which allows skilled players to differentiate between areas of importance without scanning the whole scene (Mann et al., 2019; Williams and Jackson, 2019).

The shorter total fixation times produced by the skilled group corroborates previous studies in this field which demonstrate that skilled decision-makers develop memory skills that both promote rapid encoding of information in long-term memory and afford selective access to that information when required (Gegenfurtner et al., 2011; Roca et al., 2011, 2014). This means skilled athletes develop more flexible and detailed memory representations than less skilled individuals, allowing them to adapt rapidly to changes in situational demands (Silva et al., 2010).

When measuring performance in junior athletes, the stability of a variable (maintenance of relative rankings over time) is significant for long-term talent prediction. Decision-making accuracy was examined at the follow-up testing session to identify any changes that may have occurred relative to initial testing. Given the additional 18 months of training and practice, it is not surprising that the follow-up group had a higher accuracy score when compared to their previous testing. What is of importance is that regardless of improved response accuracy, the fundamental perceptual-cognitive characteristics remained stable across time. That is, the skilled participants within the follow-up group had a visual search strategy involving fewer fixations and shorter total fixation duration times, similar to the pattern observed in the initial test. The stability of the visual search strategy in the skilled performers over time is unlike physical performance measures, which do not demonstrate stable markers and are less reliable from pre to post-maturation (Cripps et al., 2017). The relatively stable perceptual-cognitive characteristics corroborate

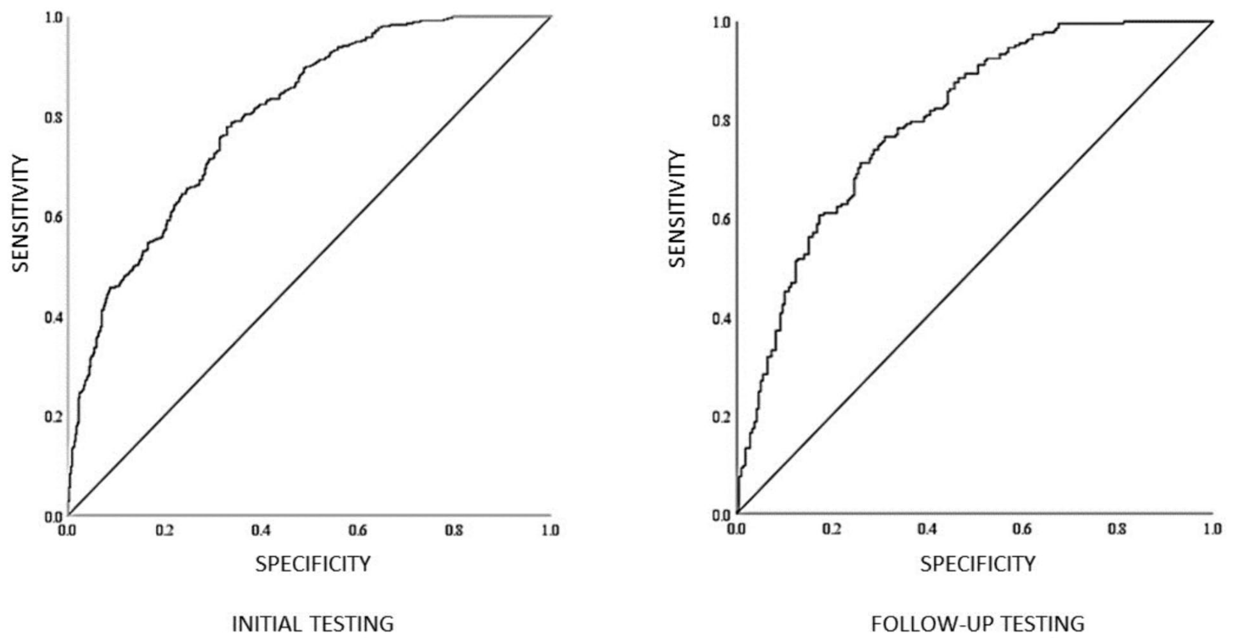


FIGURE 5
An example of an AUC graph generated from the initial and follow-up data.

previous findings that indicate perceptual-cognitive ability is a by-product of typical training activities such as on-field drills, game simulations, and tactical sessions, e.g., strategic team planning sessions, and not maturation (Williams et al., 2011; Roca et al., 2014).

The ROC analyses also show that the combination of the number of fixations, total duration of fixation, and decision time for the video-based decision-making performance provided an excellent ability to classify players as skilled or unskilled decision-makers. Indeed, Farahani et al. (2020) showed that discrimination between similar skill levels of players was possible when using response time, but not when relying on decision accuracy. Similarly, Dong et al. (2023) show that video-based decision testing may test declarative game knowledge rather than decision-making *per se*. The absence of a perception-action link in the video-based decision-making paradigm is a limitation. It should also be noted, however, that recent literature is inconclusive regarding the superiority of perception-action coupling over perception-only tasks in testing performance capabilities (see Huesmann et al., 2021; Kalén et al., 2021). However, we suggest that testing declarative game knowledge is useful for development athletes, particularly if it can discriminate between skill levels while complementing other tools and not adding to physical testing. As Américo et al. (2017) showed, game knowledge is still developing in junior team-sport athletes.

To examine potential changes in decision-making performance and development over time, we examined descriptive data to compare categorization of players based on decision-making skill at follow-up like that done during the initial testing. This allowed us to compare if players remained in a skilled or less skilled group or changed between testing sessions. Of the 11 players categorized as skilled in initial testing, five performed at a skilled level in the follow-up testing. Of the seven less skilled decision makers who were tested at follow-up, only two remained classified as less skilled, with the remaining five performing better at follow-up. It should be noted, however, that there was a higher accuracy in the follow-up skilled group (78.33%) compared to the percentage for those in the skilled group (70.43%) at initial testing. These comparisons provide some context, however, the data should not be overinterpreted, given the smaller sample at the follow-up testing, thus changes in the comparison pool between initial testing ($n = 59$) and follow-up ($n = 18$). Nevertheless, changes in performance between testing sessions are expected. For example, we expected a level of familiarity with the test at the follow-up test point however, as Dong et al. (2023) point out, even if declarative game knowledge was tested, it is appropriate that this should develop, and facilitate athletes when working with coaches, game plans, and video review sessions. These are worthy assessments for TID and allow a means to identify aspects of players' potential ability. Additional support for this rationale was found in studies that used a within-group comparison and revealed differences in football players (Vaeyens et al., 2007; Savelsbergh et al., 2010).

While the study was limited to junior male athletes, given the study goals, future research should use longitudinal measures to track both male and female elite junior athletes as they transition into elite senior athletes and measure changes to perceptual-cognitive characteristics. This will enable comparison between sex, where there may be differences in the level of exposure to overall sports training, including decision-making training, and resourcing for academy systems (see MacMahon et al., 2024 for a discussion of the development of expertise in females). A longitudinal approach can also compare drafted vs. non-drafted players and provide greater insight into whether the stability of eye-movement behavior is a key distinguisher. Further, the current study used a film-based task which as acknowledged, may not reflect on-field abilities thus studies that include *in situ* designs will provide deeper knowledge on this topic (Araujo et al., 2006). Lorains et al. (2013) created a custom-designed decision-making notational analysis system to examine the transfer of video-based training to on field competitions. The system considered game context, decision-making (quality, number of options, pressure), and execution (disposal type, effectiveness, error direction) in its performance analysis. In the Lorains et al. (2013) study, the notational analysis was used to compare film-based training to on field performance. Given Lorains et al.'s small sample size, the results are limited, thus future research should look to develop a transfer test in conjunction with film-based objective tools when assessing tactical skill components within AR football. While no significant transfer effects were present in Lorains et al., developing the research in this way is promising.

To conclude, the skills needed to achieve excellence in invasion ball sports are complex and multifaceted, highlighting the importance but also the challenges associated with developing comprehensive and objective TID assessment tools that consider all determinants of gameplay. This study was able to show a viable method for initial screening to identify the key stable visual search behaviors used by junior AR football players for declarative game knowledge and decision-making using the same film-based protocol applied to elite senior players. Further, the visual search characteristics were shown to be a strong, stable marker across time, suggesting that they may be used to objectively measure the tactical skill processes for AR football. This method, in addition to couple skill tests that require perception-action coupling under temporal constraints, can thereby be used to identify players with an elevated level of decision-making and processing skill.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Western Sydney University Human Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

KS: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. LK: Writing – review & editing, Writing – original draft, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. SD: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation. BP: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis. JQ: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. CM: Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. Funding provided by the Western Sydney University, Greater Western Sydney Australian Rules Football Club and Skins compression clothing. LK was partially supported by a scholarship between GWS, WSU and Skins to conduct eye-movement research for her PhD. The funders were not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

Acknowledgments

The authors would like to thank the Greater Western Sydney Giants Australian Football Club for their support and assistance with data collection. We would like to thank Paul Fahey for his assistance in the analysis of the data in this paper.

Conflict of interest

JQ was employed by Greater Western Sydney Giants AFL, Sydney, and Quinn Elite Sport Services, Sydney.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

References

Abernethy, B. (1990). Expertise, visual search, and information pick-up in squash. *Perception* 19, 63–77. doi: 10.1068/p190063

Afonso, J., Garganta, J., McRobert, A., Williams, M., and Mesquita, I. (2014). Visual search behaviours and verbal reports during film-based and in situ representative tasks in volleyball. *Eur. J. Sport Sci.* 14, 177–184. doi: 10.1080/17461391.2012.730064

Allard, F., and Starkes, J. L. (1980). Perception in sport: volleyball. *J. Sport Psychol.* 2, 22–33. doi: 10.1123/jsp.2.1.22

Américo, H. B., Kowalski, M., Cardoso, F., Kunrath, C. A., González-Víllora, S., and Teoldo, I. (2017). Difference in declarative tactical knowledge between U-11 and U-15 soccer players. *Human Movement Special Issues* 2017, 25–30.

Araujo, D., Davids, K., and Hristovski, R. (2006). The ecological dynamics of decision making in sport. *Psychol. Sport Exerc.* 7, 653–676. doi: 10.1016/j.psychsport.2006.07.002

Beunen, G., Thomis, M., Maes, H., Loos, R., Malina, R., Claessens, A., et al. (2000). Genetic variance of adolescent growth in stature. *Ann. Hum. Biol.* 27, 173–186. doi: 10.1080/030144600282280

Brams, S., Ziv, G., Levin, O., Spitz, J., Wagemans, J., Williams, A. M., et al. (2019). The relationship between gaze behavior, expertise, and performance: a systematic review. *Psychol. Bull.* 145, 980–1027. doi: 10.1037/bul0000207

Bruce, L., Farrow, D., Raynor, A., and Mann, D. (2012). But I can't pass that far! The influence of motor skill on decision making. *Psychol. Sport Exerc.* 13, 152–161. doi: 10.1016/j.psychsport.2011.10.005

Burgess, D., Naughton, G., and Hopkins, W. (2012). Draft-camp predictors of subsequent career success in the Australian football league. *J. Sci. Med. Sport* 15, 561–567. doi: 10.1016/j.jsams.2012.01.006

Cardoso, F. D. S. L., Afonso, J., Roca, A., and Teoldo, I. (2021). The association between perceptual-cognitive processes and response time in decision making in young soccer players. *J. Sports Sci.* 39, 926–935. doi: 10.1080/02640414.2020.1851901

Cripps, A. J., Joyce, C., Woods, C. T., and Hopper, L. S. (2017). Biological maturity and the anthropometric, physical, and technical assessment of talent identified U16 Australian footballers. *Int. J. Sports Sci. Coach.* 12, 344–350. doi: 10.1177/1747954117710507

Dicks, M., Araújo, D., and van der Kamp, J. (2019). "Perception-action for the study of anticipation and decision making" in *Anticipation and decision making in sport*. eds. A. M. Williams and R. C. Jackson (London: Routledge), 181–199.

Dong, L., Berryman, N., and Romeas, T. (2023). Questioning the validity and reliability of using a video-based test to assess decision making among female and male water polo players. *Int. J. Sports Sci. Coach.* 19:17479541231170278. doi: 10.1177/17479541231170278

Ericsson, K. A., Krampe, R. T., and Tesch-Römer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychol. Rev.* 100, 363–406. doi: 10.1037/0033-295X.100.3.363

Falk, B., Lidor, R., Lander, Y., and Lang, B. (2004). Talent identification and early development of elite water-polo players: a 2-year follow-up study. *J. Sports Sci.* 22, 347–355. doi: 10.1080/02640410310001641566

Farahani, J., Soltani, P., and Roberts, R. E. (2020). Expertise differences in a 2D animation simulation decision-making task: The influence of presentation speed on performance. *Prog. Brain Res.* 253, 87–100.

Farrow, D., Pyne, D., and Gabbett, T. (2008). Skill and physiological demands of open and closed training drills in Australian football. *Int. J. Sports Sci. Coach.* 3, 489–499. doi: 10.1260/174795408787186512

Farrow, D., and Raab, M. (2008). "A recipe for expert decision making" in *Developing sport expertise: researchers and coaches put theory into practice*. eds. D. Farrow, J. Baker and C. MacMahon (London: Routledge), 137–159.

Ford, P. R., Ward, P., Hodges, N. J., and Williams, A. M. (2009). The role of deliberate practice and play in career progression in sport: the early engagement hypothesis. *High Abil. Stud.* 20, 65–75. doi: 10.1080/13598130902860721

Gegenfurtner, A., Lehtinen, E., and Säljö, R. (2011). Expertise differences in the comprehension of visualizations: A meta-analysis of eye-tracking research in professional domains. *Educ. Psychol. Rev.* 23, 523–552.

Gogos, B. J., Larkin, P., Haycraft, J. A., Collier, N. F., and Robertson, S. (2020). Combine performance, draft position and playing position are poor predictors of player career outcomes in the Australian football league. *PLoS One* 15:e0234400. doi: 10.1371/journal.pone.0234400

Gréhaigne, J.-F., Godbout, P., and Bouthier, D. (2001). The teaching and learning of decision making in team sports. *Quest* 53, 59–76. doi: 10.1080/00336297.2001.10491730

Güllich, A., and Emrich, E. (2006). Evaluation of the support of young athletes in the elite sports system. *Eur. J. Sport Soc.* 3, 85–108. doi: 10.1080/16138171.2006.11687783

Güllich, A., and Emrich, E. (2012). Individualistic and collectivistic approach in athlete support programmes in the German high-performance sport system. *Eur. J. Sport Soc.* 9, 243–268. doi: 10.1080/16138171.2012.11687900

Huesmann, K., Loffing, F., Büsch, D., Schorer, J., and Hagemann, N. (2021). Varying degrees of perception-action coupling and anticipation in handball goalkeeping. *J. Mot. Behav.* 54, 391–400. doi: 10.1080/00222895.2021.1984868

Johnston, K., Wattie, N., Schorer, J., and Baker, J. (2018). Talent identification in sport: a systematic review. *Sports Med.* 48, 97–109. doi: 10.1007/s40279-017-0803-2

Kalén, A., Bisagno, E., Musculus, L., Raab, M., Pérez-Ferreirós, A., Williams, A. M., et al. (2021). The role of domain-specific and domain-general cognitive functions and skills in sports performance: a meta-analysis. *Psychol. Bull.* 147, 1290–1308. doi: 10.1037/bul0000355

Kelly, A. L., Finnegan, L., Till, K., and Smith, K. L. (2024). "Relative age effects: looking Back and moving forward" in *Talent identification and development in youth soccer* (London: Routledge), 132–151.

Larkin, P., Marchant, D., Syder, A., and Farrow, D. (2020). An eye for talent: the recruiters' role in the Australian football talent pathway. *PloS One* 15:e0241307. doi: 10.1371/journal.pone.0241307

Laurent, E., Ward, P., Mark Williams, A., and Ripoll, H. (2006). Expertise in basketball modifies perceptual discrimination abilities, underlying cognitive processes, and visual behaviours. *Vis. Cogn.* 13, 247–271. doi: 10.1080/13506280544000020

Light, R., and Harvey, S. (2019). *Positive pedagogy for sport coaching: Athlete-centred coaching for individual sports*. London: Routledge.

Lorains, M., Ball, K., and MacMahon, C. (2013). Performance analysis for decision making in team sports. *Int. J. Perform. Anal. Sport* 13, 110–119. doi: 10.1080/24748668.2013.11868635

MacMahon, C., Bailey, A., Croser, M., and Weissensteiner, J. (2019). Exploring the skill of recruiting in the Australian football league. *Int. J. Sports Sci. Coach.* 14, 72–81. doi: 10.1177/1747954118809775

MacMahon, C., Clarke, A., Leabeater, A., and Roberts, A. (2024). "Female sport expertise through a skill acquisition lens: a key future direction" in *Developing sport expertise: Researchers and coaches put theory into practice*. eds. D. Farrow, J. Baker and C. MacMahon. *3rd* ed (London: Routledge), 143–153.

Mandrekar, J. N. (2010). Receiver operating characteristic curve in diagnostic test assessment. *J. Thorac. Oncol.* 5, 1315–1316. doi: 10.1097/JTO.0b013e3181ec173d

Mann, D. L., Causer, J., Nakamoto, H., and Runswick, O. R. (2019). "Visual search behaviors in expert perceptual judgements" in *Anticipation and decision making in sport*. eds. A. M. Williams and R. C. Jackson (London: Routledge), 59–78.

Matthys, S. (2012). *Talent identification, development and selection in youth handball players: contribution of cross-sectional and longitudinal measures of anthropometry, physical performance and maturation* Doctoral dissertation: Ghent University.

Roca, A., Ford, P. R., McRobert, A. P., and Williams, A. M. (2011). Identifying the processes underpinning anticipation and decision-making in a dynamic time-constrained task. *Cogn. Process.* 12, 301–310. doi: 10.1007/s10339-011-0392-1

Roca, A., Williams, A. M., and Ford, P. R. (2014). Capturing and testing perceptual-cognitive expertise: a comparison of stationary and movement response methods. *Behav. Res. Methods* 46, 173–177. doi: 10.3758/s13428-013-0359-5

Savelsbergh, G. J., Haans, S. H., Kooijman, M. K., and van Kampen, P. M. (2010). A method to identify talent: Visual search locomotion behavior in young football players. *Hum. Mov. Sci.* 29, 764–776.

Silva, M. C., Figueiredo, A. J., Simoes, F., Seabra, A., Natal, A., Vaeyens, R., et al. (2010). Discrimination of u-14 soccer players by level and position. *Int. J. Sports Med.* 31, 790–796. doi: 10.1055/s-0030-1263139

Vaeyens, R., Lenoir, M., Williams, A. M., Mazyn, L., and Philippaerts, R. M. (2007). The effects of task constraints on visual search behavior and decision-making skill in youth soccer players. *J. Sport Exerc. Psychol.* 29, 147–169.

Vater, C., Williams, A. M., and Hossner, E.-J. (2020). What do we see out of the corner of our eye? The role of visual pivots and gaze anchors in sport. *Int. Rev. Sport Exerc. Psychol.* 13, 81–103. doi: 10.1080/1750984X.2019.1582082

Vitor de Assis, J., González-Víllora, S., Clemente, F. M., Cardoso, F., and Teoldo, I. (2020). Do youth soccer players with different tactical behaviour also perform differently in decision-making and visual search strategies? *Int. J. Perform. Anal. Sport* 20, 1143–1156. doi: 10.1080/24748668.2020.1838784

Williams, A. M., Ford, P. R., Eccles, D. W., and Ward, P. (2011). Perceptual-cognitive expertise in sport and its acquisition: implications for applied cognitive psychology. *Appl. Cogn. Psychol.* 25, 432–442. doi: 10.1002/acp.1710

Williams, A. M., and Jackson, R. C. (2019). *Anticipation and decision-making in sport*. London: Routledge.

Williams, A. M., and Ward, P. (2007). "Anticipation and decision making: Exploring new horizons," In *Handbook of sport psychology* (3rd ed.). Chichester: John Wiley & Sons, Inc., 203–223.

Wolstencroft, E., and House, C. (2002). *Talent identification and development: an academic review*. Edinburgh: Sport Scotland.

Woods, C. T., Raynor, A. J., Bruce, L., McDonald, Z., and Collier, N. (2015). Predicting playing status in junior Australian football using physical and anthropometric parameters. *J. Sci. Med. Sport* 18, 225–229. doi: 10.1016/j.jsams.2014.02.006

Woods, C. T., Raynor, A. J., Bruce, L., McDonald, Z., and Robertson, S. (2016). The application of a multi-dimensional assessment approach to talent identification in Australian football. *J. Sports Sci.* 34, 1340–1345. doi: 10.1080/02640414.2016.1142668

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 11 June 2024
DOI 10.3389/fpsyg.2024.1356892

Check for updates

OPEN ACCESS

EDITED BY
Karen Zentgraf,
Goethe University Frankfurt, Germany

REVIEWED BY
Thomas Muehlbauer,
University of Duisburg-Essen, Germany
Marie-Therese Fleddermann,
Goethe University Frankfurt, Germany

*CORRESPONDENCE
Thomas J. Klotzbier
✉ thomas.klotzbier@inspo.uni-stuttgart.de

RECEIVED 16 December 2023
ACCEPTED 08 May 2024
PUBLISHED 11 June 2024

CITATION
Klotzbier TJ and Schott N (2024) Skillful and strategic navigation in soccer – a motor-cognitive dual-task approach for the evaluation of a dribbling task under different cognitive load conditions.
Front. Psychol. 15:1356892.
doi: 10.3389/fpsyg.2024.1356892

Skillful and strategic navigation in soccer – a motor-cognitive dual-task approach for the evaluation of a dribbling task under different cognitive load conditions

Thomas J. Klotzbier* and Nadja Schott

Institute of Sport and Movement Science, Department of Sport Psychology and Human Movement Performance, University of Stuttgart, Stuttgart, Germany

Soccer is a competitive sport that relies on distinct motor skills and cognitive processes. However, cognitive aspects are often overlooked, with a focus mainly on motor skills. Limited research has explored screening tests within motor-cognitive navigation dual-task (DT) paradigms. This study aims to validate a sensitive approach for assessing soccer-specific dribbling by evaluating the Trail-Dribbling Test (TDT) as a method to differentiate high-performance (HP) from low-performance (LP) players. Two hundred and seventy-five participants (41 females) aged between 12 and 34 completed the Trail-Making Test (TMT), the Trail-Walking Test (TWT), and the soccer-specific TDT under three levels of cognitive load. Results indicated shorter TDT durations for HP compared to LP players, with increased cognitive load accentuating differences (TDT-M: $p = 0.044$, $d = 0.260$; TDT-A: $p < 0.001$, $d = 0.449$; TDT-B: $p < 0.001$, $d = 0.653$). The TDT effectively discriminated between HP and LP players in the 14–15 (AUC = 0.712–0.820) and 16–17 age groups (AUC = 0.634–0.839). In conclusion, the ecologically valid TDT demonstrates the potential for quantifying soccer-specific dribbling, offering insights into motor and cognitive aspects of dribbling performance, especially among soccer players aged 14–17.

KEYWORDS

soccer-dribbling, navigation, spatial abilities, motor-cognitive interference, assessment

1 Introduction

Soccer is defined by various specific features and characteristics, such as the specificity and volume of practice, as well as the constraints on performers, including psychological factors, technical and tactical skills, and anthropometric and physiological factors. Additionally, environmental constraints and socio-cultural influences play a significant role (Sarmento et al., 2018). Psychologists and sports scientists employ a wide range of diagnostic tests, ranging from simple to highly complex, to assess different aspects of these cognitive and motor skills. A detailed analysis of the essential characteristics of soccer supports this classification. Soccer is a complex and highly dynamic sport with constantly changing game situations, placing it in the 'Open Skill Games' category on the continuum between 'open' and 'closed' skills (Carling et al., 2007; Nuri et al., 2013). Although certain situations, such as free kicks, corner kicks, kick-offs, and penalty kicks, involve "closed" skills, the majority of skills are performed in complex and changing scenarios. Like most sports games, soccer requires the simultaneous execution of both motor and cognitive skills (Campos, 1993; Casanova et al., 2009). Players must absorb and process relevant information to make effective decisions and plans of action based on their abilities while also possessing the ability to anticipate the game (Williams, 2000). Perceptual tasks, such as tracking the ball and the movements of teammates and opponents, assessing player positions on the field, understanding tactical alignment, interpreting the coach's instructions, and considering the current game situation, must be integrated into their decision-making processes and action plans (Sakamoto et al., 2018). However, when it comes to assessing motor skills, these aspects have rarely been considered.

1.1 Cognitive test procedures

Ali (2011) provides an interesting review of cognitive and motor test procedures in soccer, identifying strengths and weaknesses and offering methodological testing recommendations. Two approaches can be identified regarding the cognitive tests discussed in the review. The first approach, the "Cognitive Component Skill Approach," focuses on general cognitive skills that differentiate experts from novices. This approach often utilizes paper-pencil methods or computer-based reaction time experiments. While these methods offer high internal validity, they may be limited in ecological validity and their ability to quantify the intricate cognitive processes during a soccer game. Consequently, sports training is viewed as cognitive training, leading to structural and functional adaptations that enhance cognitive performance (referred to as the "Cardiovascular Fitness Hypothesis"; Aberg et al., 2009; see also Audiffren and André, 2019). However, Beavan et al. (2020a,b) have questioned this approach, particularly the relationship between sport-specific experience and cognitive skills. They raise concerns about incorporating cognitive skills in the process of talent identification. An alternative approach is the "Expert Performance Approach," which assesses athletes in ecologically valid contexts using tasks that are representative of their specific domain. Mann et al. (2007) conducted a meta-analysis demonstrating that experts recognize domain-specific cues faster and process them more effectively. Experts also exhibit different strategies in visual search tasks than novices, showing fewer fixations (saccade jumps) of longer duration. These tests often involve video-based experiments or simulations of game situations that may not necessarily be observed from a first-person perspective. However, it is important to consider that decision-making and anticipation processes may differ fundamentally in real-game situations, raising questions about the transferability of this methodological approach (Roca et al., 2011). Furthermore, determining correct answers in these tests could rely on the subjective decisions of trainers, researchers, or test administrators. A possible transfer effect as well as the dependence on subjective decisions about correct answers necessitate further research efforts.

Musculus et al. (2022) and Knöbel and Lautenbach (2023) aimed to combine the strengths of both approaches to develop and validate cognitive tasks for measuring inhibition, cognitive flexibility, and working memory in a soccer-specific context. The tasks were paired with a soccer-specific motor response (i.e., pass). The authors suggest that utilizing this approach allows for an effective assessment of core executive functions. They propose that these tasks could serve as a reliable cognitive diagnostic tool for soccer clubs.

1.2 Assessing relevant soccer-specific motor skills for talent diagnostics

Procedures for assessing motor skills in soccer often focus on isolating specific aspects, such as passing or shooting, typically in static or otherwise controlled situations. However, according to Ali (2011), the cognitive component is a fundamental part of a skill, encompassing decision-making and information processing. Unfortunately, many tests tend to neglect this cognitive component, which raises doubts about their ecological validity, as per Ali's (2011) definition of skills.

When conducting talent research, it is crucial to consider not only the quality of test procedures used to assess cognitive and motor skills but also which characteristics are considered relevant (Williams and Reilly, 2000; Kannekens et al., 2011). Talent development is a multifactorial process that depends on a variety of individual factors and environmental factors (Murr et al., 2018). This raises the question of which criteria are crucial for identifying talents and how these requirements should be specified. It is important to note that this requirement profile is position-specific. For example, the ability to score goals may be highly relevant for a striker but considered less critical for a defender. There are also numerous examples of exceptional soccer players, such as Lionel Messi or Andres Iniesta, who excel in the sport despite not possessing exceptional heading skills. Therefore, this study introduces a test procedure to quantify dribbling as a vital component in soccer.

1.3 Integration of motor and cognitive components in navigation (dual) tasks

Dual-task (DT) paradigms provide a valuable opportunity to integrate the cognitive component and combine motor and cognitive tasks (see Box 1). From a methodological perspective, cognitive-motor interference has seldom been studied in physical environments with high variability of spatial movements (Smith and Chamberlin, 1992; Beilock et al., 2002). Previous studies have mainly focused on ecologically less valid laboratory situations, such as straight-ahead walking on a treadmill or at ground level, which reduces the demands on physical navigation (Moreira et al., 2021). Treadmills are valuable tools for analyzing gait kinematics during continuous walking (e.g., Padulo et al., 2014). However, they only allow for straight-line walking, which is a mechanical and continuous motor act that does not require the same level of attention to the environment as walking in everyday situations or during sports. Visual input is crucial in the interplay between the body and the environment (Imai et al., 2001). However, comprehensive situational awareness, spatial orientation, and the ability to move freely in three-dimensional space are also essential for successful action in ball sports (Woods et al., 2020; Bartseva et al., 2024).

In sports, players often navigate from point A to point B, constantly directed toward a physical object (e.g., the ball, a

BOX 1 A critical view and alternative perspectives on constructing DT paradigms.

Multitasking is a broad concept that can be measured in various ways (Kiesel et al., 2022). It involves performing multiple tasks, each associated with a separate task set, within a limited period of time, resulting in a temporal overlap of cognitive processes (Koch et al., 2018). A task can be defined as an abstract description of a future state or a desired goal. It can be instructed, where task sequences are predetermined, or self-organized, where they are functionally interdependent (e.g., wayfinding) or independent (e.g., continuous motor task and counting backward in steps of 3; Künzell et al., 2018; Strayer et al., 2022). Furthermore, a task set refers to a representation of the cognitive and motor requirements necessary to perform a task (Koch et al., 2018).

Temporal overlaps of cognitive processes can occur during the execution of multiple tasks, such as in task switching (i.e., sequential multitasking) and dual-tasking (i.e., simultaneous multitasking). Sequential multitasking involves performing one task for an extended period before switching to another task. This can range from several minutes, such as walking while having a conversation, to even hours, such as cooking and reading a book (Salvucci and Taatgen, 2011). However, in concurrent multitasking, tasks are performed simultaneously or with frequent switches between them in short periods of less than 1 min. This can result in lower performance in one or both tasks (Koch et al., 2018).

McIsaac et al. (2015) propose a standardized classification system for tasks in motor-cognitive dual-task paradigms. They define a dual-task as two separate tasks with different goals that are functionally independent of each other (see also Strayer et al., 2022). They have different goals (e.g., walking vs. talking) with different stimuli (the environment vs. the content of the conversation) and responses (e.g., avoiding an obstacle vs. speaking and listening). It is crucial to note that the performance of each task can be evaluated separately. We critically question McIsaac's taxonomy and discuss the nature and construction of DTs without prescribing a single standard for their design.

Our approach is based on the idea that it is not possible to completely neglect one task when people are asked to perform two tasks simultaneously, such as walking and counting backward. This is especially important considering the importance that participants attribute to the cognitive task. This discovery presents a challenge for designing DT experiments and emphasizes the constraints of previous research methods, especially regarding common daily situations that frequently involve interdependent tasks. For instance, when driving through an unfamiliar area, it is important to be able to follow navigation instructions simultaneously. This is a situation in which cognitive processes must perform multiple tasks in parallel or at least partially in parallel (Koch et al., 2018). Unlike functionally independent tasks, where one task can be neglected, the Trail Dribbling Test used here emphasizes the need to pay attention to both tasks.

For instance, a player could dribble to the letter B while simultaneously performing a visual search for the number 3. While dribbling, the cognitive task can be neglected, and the motor component of dribbling to be impaired while moving slowly and searching visually. However, it is important to integrate both tasks into a coherent action plan that allows the player to continue searching for the next number while dribbling. Experienced players are more likely to achieve this, particularly if dribbling is automatic and there are enough cognitive resources for both tasks. Additionally, motor and cognitive tasks can be scored separately, such as dribbling through the parkours versus reciting or showing the Trail Making Test conditions A and B with a laser pointer. By calculating the dual-task costs (DTC), it is possible to examine the distribution of resources between the tasks.

Overall, we believe that the definition of what constitutes DT remains subject to interpretation, lacking a universally accepted standard for their design.

teammate) or a place (e.g., our own or the opponent's goal) to perform a specific action (e.g., pass, shot on goal). The term "navigation" is defined as coordinated and goal-oriented movement through space, which is made up of two components: Wayfinding and Locomotion (Montello, 2005; Wiener et al., 2009). Wayfinding is the planning and problem-solving part of navigation in which decisions are made. This involves planning and deciding on a series of actions (e.g., "pass to teammate" + "run deception" + "run into the free gap") based on available information and existing knowledge about the space. To do this, one refers to internal (existing knowledge about the space [e.g., the soccer field] in your head) or external knowledge (e.g., specific moves). During "route planning," individuals tend to identify potential running paths that match their goals and then use various implicit and explicit strategies to quickly reduce the options and settle on a route (e.g., a direct running path to the goal). During the execution of the plan – the locomotion – it is constantly reviewed based on the newly received information from the environment and, if necessary, adjusted (e.g., when a free gap closes) (Montello, 2005; Yang et al., 2018). The locomotion is the pure movement through space in the direction specified by the plan. During this movement, the immediate surroundings are primarily perceived to avoid possible obstacles. Although these two components can be described separately, they rarely occur independently and can, therefore, be described as a dual task (Brunyé et al., 2018). Separating locomotion and wayfinding only occurs when walking aimlessly or planning a game move that is not executed (Montello and Sas, 2006). Thus, successful navigation involves efficiently reaching a specific destination without causing physical harm. This requires awareness of one's location in relation to the destination and other places or objects while in motion.

In the context of soccer-specific navigation, two intriguing studies have been conducted that address distinct research questions while incorporating both motor and cognitive demands in a DT dribbling test. Smith and Chamberlin (1992) asked female soccer players of varying performance levels to complete three different conditions. Participants were instructed to complete a slalom course emphasizing running agility in the first condition. The goal was to finish as quickly as possible without dribbling a soccer ball. In the second condition, participants had to dribble through the course as rapidly as possible. In the third condition, participants had to identify various symbols displayed on a screen while simultaneously performing the dribbling task. Comparing the three groups, experts demonstrated significantly less interference than the other groups. The differences between the expert groups became more pronounced when the cognitive component was performed in parallel with the motor task. In the second study by Beilock et al. (2002), dribbling was explored as a motor skill within a DT paradigm and involved two groups: experts and novices. Both groups were tasked with dribbling the ball through a slalom course using either their dominant or non-dominant foot while simultaneously performing additional cognitive tasks. These tasks included identifying auditory stimuli or directing attention solely to dribbling (skill-focused). The results of the study indicated that completing the DTs took longer for both groups, with one notable exception: the expert group exhibited faster performance when dribbling with their dominant leg. Interestingly, in the skill-focused attention condition, both experienced and novice participants dribbled at a more similar speed. The contrast between the two groups became more evident during the DT condition, especially when dribbling with the dominant leg. This highlights that experienced performers demonstrated a significant speed advantage over novices in the DT condition. However, in the skill-focused condition, this advantage was considerably diminished when dribbling with the dominant leg. In summary, the study showed that experienced soccer players performed notably faster in the DT condition compared to the skill-focused condition, while novices displayed a tendency toward the opposite pattern, dribbling faster in the skill-focused condition than in the DT condition.

These two studies are intriguing because they separate cognitive (wayfinding) and motor tasks (dribbling), allowing them to be performed independently. This creates the possibility of prioritizing one task over the other, potentially neglecting one of the two. In addition, both studies (Smith and Chamberlin, 1992; Beilock et al., 2002) used non-soccer-related cognitive tasks without direct reference to the dribbling task. In terms of the navigation required in soccer, a dual task that establishes a greater connection to soccer-specific path planning and execution would, therefore, be advantageous. An elegant way to test visual–spatial abilities with different cognitive loads in a soccer-related navigation task is provided by the adaptation of the Trail-Walking Test (TWT; Schott, 2015). In this study, we employ both non-soccer-specific tasks (TWT) and a soccer-specific adaptation of the TWT (Trail-Dribbling Test; TDT).

The overall goals of this study were (1) to investigate the feasibility of differentiating performance groups (novices vs. experts) using two different navigational DTs that vary in their degree of specificity to soccer, and (2) to determine the specific age ranges in which differentiation between the performance groups is possible, and (3) to evaluate the sensitivity and specificity of this differentiation. It was hypothesized that varying levels of interference would occur depending on the specificity of the tasks and that a soccer-specific skill would be more likely to differentiate between younger high-performance (HP-SP) and low-performance soccer players (LP-SP). Specifically, it is assumed that as the cognitive load of the navigation (dual) tasks increases, the differences between HP-SP and LP-SP would become more pronounced, particularly in soccer-specific tasks, compared to situations with low cognitive load and soccer-unspecific tasks.

2 Methods

2.1 Sample size estimation

Power analysis [using G*Power3; a statistical power analysis program (Faul et al., 2007)] was conducted to estimate the necessary sample size. In our ANCOVA analysis with repeated measures with one covariate, we aimed for a 95% power, an effect size of $f = 0.25$, and a significance level of $p = 0.05$ to identify fixed, main, and interaction effects. The calculated sample size needed was 251 participants. Our sample size of 275 exceeds the necessary number, ensuring our desired statistical power and confidence level.

A power analysis (Superpower; Caldwell and Lakens, 2019) was conducted on a 2(group) x 2(domain) x 3(condition) ANOVA with repeated measures design with 20 participants per cell (12 cells in our design). Assuming a high effect size of $f = 0.4$, a standard deviation of 1.0, a correlation of 0.5, and an alpha of 0.05, a power of 100% was found for the main effect of group, a power of 100% for the main effect of condition, a power of 81.1% for the main effect of domain, a power of 6.3% for the interaction effect of group x condition, 5.6% for the interaction effect of group x domain, 5.5% for condition x domain, and 5.7% for the three-way interaction of group x condition x domain. Due to the limited power for detecting interaction effects within our analyses, we can only provide reliable statements regarding the main effects, which aligns with the recommendation made by Brysbaert (2019).

2.2 Participants

The players were recruited from amateur and professional soccer clubs across Germany, including players from the youth development centers of top-class clubs such as VfB Stuttgart or FC Schalke 04. The participants were primarily recruited from clubs in the Stuttgart region. All potential participants from the mentioned clubs who volunteered to participate in the study were included. Individuals with motor or cognitive impairments were excluded. Swann et al. (2015) developed a classification system based on the athlete's highest level of performance, success, experience, and competitiveness (national and global). This system categorizes players into four levels of elite competitive athletes. Key variables of their definition are the highest standard of performance as well as success and experience at the athlete's highest level. Since this is aggregated data from various surveys, not all participants were initially queried on these essential variables for Swann's categorization. However, we were able to determine the competition level for all participants. Depending on the competition level, participants were assigned to either the high-performance (HP) or low-performance (LP) group: Participants playing in an active adult team at the "Landesliga" (1st to 6th division) level or above were assigned to the HP group. In contrast, those playing below the "Bezirksliga" (8th + division) level were assigned to the LP group. In youth teams, participants playing in the "Verbandsliga" were assigned to the HP group, while those below the "Bezirksliga" level were assigned to the LP group. Athletes who had previously played at a high level but were not actively playing soccer were excluded.

2.3 Instruments

2.3.1 Cognitive control

The Trail-Making Test (TMT; Reitan, 1958) assesses cognitive processing speed, executive functions, and attentional components (Salthouse, 2011). The test comprises of two parts. In part A, the test subjects are to connect circles numbered from 1 to 25 in ascending order and as quickly as possible. In part B, the test subjects are to connect the numbers 1 to 13 and the letters from A to L alternately in ascending order and at maximum speed. Furthermore, a motor speed-tracking task measures the participant's fine-motor performance (Schott et al., 2016). The task records the time taken and the number of errors made. Any shifting and sequential errors are immediately corrected by the examiner, who instructs the participant to return to the last correct circle. Therefore, errors are factored into the required times as correcting errors takes additional time (Schott et al., 2016; Klotzbier et al., 2020). Each trial and sequence is carried out until the last cone is reached. The same approach concerning shifting and sequential errors is used for the two subsequent DTs.

2.3.2 Non-soccer-specific and soccer-specific dual-tasks

The Trail-Walking Test (TWT, Schott, 2015) is conducted on a 4×4 meter playing field consisting of 15 cones labeled with numbers or numbers and letters depending on the condition. In the motor condition (TWT-M), the objective is to navigate a designated path as quickly as possible. In this condition, the cones do not have any numbers or letters; only the path on the playing field is marked with chalk. In the second condition (TWT-A), participants must run to the cones in ascending numerical order (1-2-3-…-15). In the third and final condition (TWT-B), the task is to run to the cones in alternating ascending order of numbers and letters (1-A-2-B-…-8). In addition, there was another implementation format for an alternative calculation of the cognitive costs (signaling condition). Here, the participants (subsample $n = 165$) stood in the middle of the field and had to use a laser pointer to (1) trace the purely motor path, (2) connect the numbers, and (3) the numbers and book strokes as quickly as possible. The objective is to complete the course as fast as possible without making any errors. The same conditions are applied in the Trail-Dribbling Test (TDT), except participants must dribble a soccer ball through the course. All conditions' lengths are identical (41 meters) for accurate comparisons. Stopwatch measurements are used to record the times, rounded to 0.01 s. The positions of the cones placed in the field, as shown in the run schedule in Figure 1, remained the same for each condition and each trial. For the purely motor condition without soccer-specific skill (TWT-M), there was one practice session to become familiar with the run schedule. Each condition, including both the non-soccer-specific task and the soccer-specific task, was conducted three times.

2.4 Procedure

The data was collected during the teams' scheduled training sessions. Following the demographic data questionnaire, all tests and conditions (TMT, TWT, TDT) were randomized to avoid sequence effects. Each condition was conducted three times, and the mean within each condition was calculated. Data from individual trials are not accessible due to data pooling; however, we do have data from a total of 42 participants (both LP and HP) across all three trials to capture the learning effect in the TWT and TDT. A 3-min break was taken between each run to eliminate possible fatigue effects. Informed written consent was obtained from the clubs/organizations and parents/guardians before the testing. Additionally, participants provided consent and were informed of their right to withdraw from the study at any time. The informed consent was given willingly and without any coercion or bribery. All procedures adhered to the principles outlined in the Declaration of Helsinki (World Medical Association, 2013), including ethical standards, legal requirements, and international norms.

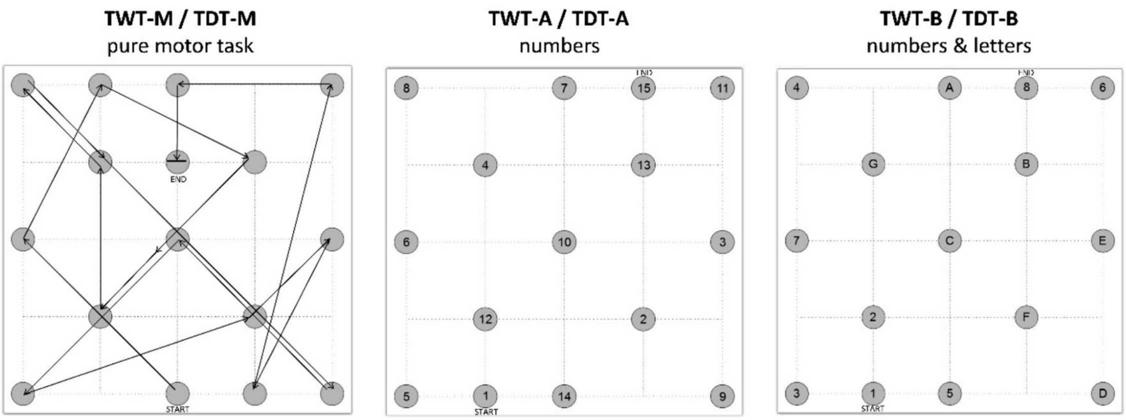


FIGURE 1
Conditions of the Trail-Walking Test and the Trail-Dribbling Test (Schott, 2015). TWT-M, Trail-Walking Test – pure motor task; TDT-M, Trail-Dribbling Test – pure motor task; TWT-A, Trail-Walking Test – numbers; TDT-A, Trail-Dribbling Test – numbers; TWT-B, Trail-Walking Test – numbers & letters; TDT-B, Trail-Dribbling Test – numbers & letters.

2.5 Data analysis

SPSS v.27 (SPSS, Chicago, IL) was used for the statistical analysis. Initially, we assessed missing data points, evaluated the normality of distributions (using Kolmogorov–Smirnov tests), and checked for extreme values in the dependent variables. A significance level of 0.05 was utilized for all statistical tests, following the guidelines of Tabachnick et al. (2013). We used Eta-squared (η^2_p) and calculated Cohen's d as effect size measures.

2.5.1 Sample characteristics

T-tests were employed for continuous variables to evaluate potential differences in baseline characteristics between groups, such as age, BMI, and years of regular training. A chi-square test was used for categorical demographic variables such as sex.

2.5.2 Velocities for the TMT

We calculated the velocities for the TMT to account for the different lengths in the conditions of the TMT (TMT-M: 185.4 cm; TMT-A: 185.4 cm and TMT-B: 243.8 cm; Gaudino et al., 1995). The absolute durations were used for the TWT conditions (TWT-M, TWT-A, and TWT-B) and the TDT conditions (TDT-M, TDT-A, and TDT-B) since the lengths are the same across conditions.

2.5.3 Dual-task costs (DTC)

The performance in each task under DT conditions is compared to the performance in the respective single-task (ST) conditions. Negative signs have been inserted to indicate poorer performance in the DT conditions compared to ST conditions. Therefore, negative DTC values represent a deterioration in performance, while positive DTC values indicate a relative improvement in performance under DT conditions (Plummer and Eskes, 2015, p. 3). Motor and cognitive DTC were computed for both the number condition and the number and letter condition in both the soccer-specific (TDT) and non-soccer-specific (TWT) tasks.

$$\text{DTC} = \frac{-\left(\text{DT performance} - \text{ST performance}\right)}{\text{ST performance}} * 100$$

To calculate the cognitive ST performance, the purely motor conditions (TWT-M or TDT-M) were subtracted from the DT conditions. This was used to obtain the time for the ST cognitive process. In addition, an alternative method for calculating cognitive DTC was used for a subsample of 165 individuals. The time required for the signaling task served as a measure of cognitive performance under ST conditions. Subsequently, the calculation of DTC was also carried out according to the formula specified above.

2.5.4 Analysis of variance

A 2 (group: LP-SP vs. HP-SP) x 3 (condition: only motor, numbers, numbers and letters) ANCOVA with repeated measurement for the calculated times in the TWT and TDT and age as covariate was performed to test the effect of the three different cognitive conditions.

For the evaluation of DTCs, a 2 (group: LP-SP vs. HP-SP) x 2 (condition: only motor, numbers, numbers and letters) x 2 (domain: motor vs. cognitive) ANCOVA with repeated measurement and age as a covariate was performed. Group differences within the conditions (e.g., TWT-M) were investigated using t-tests for independent samples (Bonferroni correction). In addition to the significance value ($p < 0.05$, *significant; $p < 0.01$; strong significant; $p < 0.001$, highly significant), the effect sizes for all ANCOVAs are given using Partial Eta Squared (η^2_p).

2.5.5 Receiver operating characteristic (ROC) analyses

Sensitivity, specificity, and the area under the curve (AUC) were considered as quality measures to evaluate the diagnostic capability of the TDT. Participants were categorized into distinct age categories: (see Table 1) to investigate the diagnostic accuracy across different age groups. The Youden index was utilized to determine the optimal threshold for distinguishing between LP and HP individuals within each age group. This index, calculated as Youden index = (sensitivity + (specificity-1)), can range from −1 to 1 (Hilden and Glasziou, 1996).

3 Results

3.1 Participants

A total of 275 participants were included in the study, comprising 234 males and 41 females. There were no significant differences in sex distribution between the groups, with a higher proportion of males in both groups. Of the participants, 242 identified soccer as their primary sport. The high-performance (HP-SP) group was significantly younger than the low-performance (LP-SP) group. The HP-SP group had a lower BMI than the LP-SP group. The HP-SP group began their regular training significantly earlier than the LP-SP group. Furthermore, the HP-SP group had more training hours in their current sport than the LP-SP group. Only 135 participants completed the Trail-Making Test (TMT) (equally distributed between the performance groups: 69 in HP-SP and 68 in LP-SP). The HP-SP group differed significantly from the LP-SP group in conditions M and A of the TMT, but no differences were observed in the condition with high cognitive load (TMT-B) (see Table 2).

The ROC analyses did not reveal any age differences between the high-performance (HP-SP) and low-performance (LP-SP) groups (see Table 1). However, there were significant differences in sex distribution between the performance groups, with a higher proportion of males than females. It is worth noting that only male participants were tested in the youngest and oldest age groups. Furthermore, it was observed that the HP-SP group had more training hours in soccer than the LP-SP group ($d = -0.928 - -6.04$).

3.2 Durations in the non-soccer-specific task (TWT) and the soccer-specific task (TDT)

3.2.1 Trail-walking test

The durations in all three conditions of the TWT and all groups were normally distributed ($p < 0.001$). Age correlated (Pearson correlation coefficient) significantly with the durations in all conditions (TWT-M: $r = -0.692$, $p < 0.001$; TWT-A: $r = -0.159$,

TABLE 1 Participant characteristics in LP-SP and HP-SP across age groups for evaluating receiver operating characteristics.

	LP-SP 12–13 (n = 26)	HP-SP 12–13 (n = 55)	LP-SP 14–15 (n = 27)	HP-SP 14–15 (n = 15)	LP-SP 16–17 (n = 9)	HP-SP 16–17 (n = 31)	LP-SP 18–24 (n = 56)	HP-SP 18–24 (n = 31)	LP-SP 25–34 (n = 15)	HP-SP 25–34 (n = 10)	Statistical analysis (n = 275)
Age (years)	12.4 (0.50)	12.5 (0.50)	14.2 (0.42)	14.3 (0.49)	16.3 (0.50)	16.4 (0.50)	21.5 (2.04)	21.0 (1.73)	28.2 (2.59)	28.5 (2.42)	$F(9,265) = 391^{***}$, $\eta^2_p = 0.930$
	$t(106) = -0.395^{ns}$		$t(40) = -0.772^{ns}$		$t(38) = -0.453^{ns}$		$t(85) = 1.11^{ns}$		$t(23) = -0.291^{ns}$		
Sex	26 ♂, 0 ♀	55 ♂, 0 ♀	14 ♂, 13 ♀	14 ♂, 1 ♀	4 ♂, 5 ♀	16 ♂, 15 ♀	53 ♂, 30 ♀	27 ♂, 4 ♀	15 ♂, 0 ♀	10 ♂, 0 ♀	$CHI^2(1) = 135.5^{***}$
	N/A		$CHI^2(1) = 7.47^{**}$		$CHI^2(1) = 0.143^{ns}$		$CHI^2(1) = 1.54^{ns}$		N/A		
BMI (kg/m²)	17.4 (1.81)	18.1 (1.87)	19.4 (2.83)	19.3 (2.20)	20.4 (2.09)	21.0 (1.39)	22.9 (1.90)	22.7 (1.59)	25.1 (1.58)	24.4 (1.95)	$F(9,242) = 38.6^{***}$, $\eta^2_p = 0.590$
	$t(106) = -0.949^{ns}$		$t(39) = 0.068^{ns}$		$t(38) = -1.08^{ns}$		$t(84) = 0.350^{ns}$		$t(23) = 0.966^{ns}$		
Age of regular training? (years)	N/A	5.56 (1.56)	9.39 (3.24)	5.47 (1.68)	10.7 (3.71)	6.20 (2.28)	7.96 (2.79)	6.38 (2.37)	8.36 (4.60)	5.56 (1.87)	$F(8,200) = 7.76^{***}$, $\eta^2_p = 0.273$
	N/A		$t(38.7) = 5.09^{***}$, $d = 1.64$		$t(9.88) = 3.43^{*}$, $d = 1.11$		$t(81) = 2.59^{*}$, $d = 0.576$		$t(21) = 1.73^{T}$, $d = 0.755$		
Amount of training in soccer (min/week);	N/A	360 (0.00)	184 (29.7)	354 (23.2)	200 (75.0)	312 (57.8)	212 (106)	316 (110)	198 (51.7)	325 (57.5)	$F(8,208) = 19.9^{***}$, $\eta^2_p = 0.434$
	N/A		$(40) = -19.1^{***}$, $d = -6.04$		$t(38) = -4.81^{***}$, $d = -1.56$		$(85) = -4.28^{***}$, $d = -0.928$		$t(23) = -5.78^{***}$, $d = -2.41$		
TMT-M (motor task)	N/A	N/A	9.39 (2.78)	6.55 (0.587)	8.16 (0.988)	6.29 (2.05)	9.19 (2.24)	8.92 (2.37)	10.5 (2.45)	9.89 (2.79)	$F(7,129) = 7.03^{***}$, $\eta^2_p = 0.276$
	N/A		$t(29.1) = 4.74^{***}$, $d = 1.76$		$t(38) = 2.64^{***}$, $d = 0.857$		$t(45) = 0.408^{ns}$		$t(16) = 0.453^{ns}$		
TMT-A (numbers)	N/A	N/A	24.7 (10.1)	21.5 (5.64)	19.3 (5.97)	19.2 (6.97)	20.2 (5.23)	17.1 (5.74)	21.6 (2.72)	17.3 (2.18)	$F(7,129) = 2.78^{T}$, $\eta^2_p = 0.131$
	N/A		$t(30) = 0.675^{ns}$		$t(38) = 0.007^{ns}$		$t(45) = 1.99^{T}$, $d = 0.593$		$t(16) = 3.62^{**}$, $d = 1.81$		
TMT-B (numbers & letters)	N/A	N/A	52.9 (15.4)	56.2 (15.6)	44.2 (11.1)	47.8 (17.0)	44.9 (12.9)	44.7 (13.4)	37.9 (5.93)	37.1 (13.2)	$F(7,129) = 2.29^{*}$, $\eta^2_p = 0.111$
	N/A		$t(30) = -0.434^{ns}$		$t(38) = -0.607^{ns}$		$t(45) = 0.049^{ns}$		$t(16) = 0.180^{ns}$		

The age ranges are also used to evaluate the TDT as a diagnostic test; N/A, not available (due to organizational constraints, capturing the TMT was not always feasible); HP-SP, high-performance soccer players; LP-SP, low-performance soccer players; NS, not significant; T, tendencially significant; $p < 0.05$, *significant; $p < 0.01$; strongly significant; $p < 0.001$, highly significant; BMI (Body Mass Index), Weight (in kilograms) / (Height (in meters) * Height (in meters)); TMT-M, Trail-Making Test – pure motor task; TMT-A, Trail-Making Test – numbers; TMT-B, Trail-Making Test – numbers & letters; η^2_p, Partial Eta Squared; ♂, male; ♀, female.

$p = 0.009$; TWT-B: $r = -0.206$, $p < 0.001$). Sex did not influence the performance in any TWT conditions (TWT-M: $p = 0.089$; TWT-A: $p = 0.079$; TWT-B: $p = 214$). The mean values of the TWT in ST and DT are shown in Figure 2 for both performance groups. Participants show improvement across the three trials and in all three conditions of the TWT (TWT-M: 14.7–14.5 – 14.3; TWT-A: 30.0–25.7 – 23.9; TWT-B: 39.2–33.4 – 31.2).

A 2 (group: HP-SP vs. LP-SP) x 3 (condition: motor, numbers, numbers and letters) ANCOVA with repeated measures of TWT durations and age as covariate showed significant main effects for condition, $F(1.57, 425) = 50.7$, $p < 0.001$, $\eta^2_p = 0.158$, and age $F(1, 270) = 43.1$, $p < 0.001$, $\eta^2_p = 0.138$. A significant group difference was not observed, $F(1, 270) = 0.827$, $p = 0.364$, $\eta^2_p = 0.003$. In addition, ANCOVA led to a significant interaction of condition x age, $F(1.57, 425) = 10.2$, $p < 0.001$, $\eta^2_p = 0.036$. The interaction condition x group was not significant, $F(1.57, 425) = 1.35$, $p = 0.256$, $\eta^2_p = 0.005$. The post-hoc analysis showed that the durations in TWT-B ($M = 36.2$, $SE = 0.597$) were significantly higher than in TWT-A ($M = 26.1$, $SE = 0.341$) or the motor (TWT-M) condition ($M = 18.0$, $SE = 0.198$) ($p < 0.001$). Also, the *post hoc* analysis showed that for the TWT-M, both groups differ significantly from each other, $t(273) = -2.72$, $p = 0.007$, $d = -0.328$.

3.2.2 Trail-dribbling test

The durations in all three conditions of the TDT and all groups were normally distributed ($p < 0.001$ – $p = 0.007$). The age correlated (Pearson correlation coefficient) significantly with the durations in the TDT-M ($r = -0.501$, $p < 0.001$) but not in the conditions with cognitive load (TDT-A: $r = -0.040$, $p = 0.254$; TDT-B: $r = -0.004$, $p = 0.473$). Sex influenced the performance in the TDT in all conditions ($p < 0.001$), where males produced lower durations in all conditions. The mean values of the TDT ST and DT conditions are shown in Figure 3 for both performance groups. Participants show improvement across the three trials and in all three conditions of the TDT (TDT-M: 19.7–19.5 – 19.0; TDT-A: 34.8–32.8 – 29.7; TDT-B: 44.0–40.3 – 36.9).

A 2 (group: HP-SP vs. HP-SP) x 3 (condition: motor, numbers, numbers, and letters) ANCOVA with repeated measures of TDT durations and age as a covariate showed significant main effects for condition, $F(1.81, 488) = 14.5$, $p < 0.001$, $\eta^2_p = 0.051$, group, $F(1, 269) = 32.1$, $p < 0.001$, $\eta^2_p = 0.107$, and age $F(1, 269) = 18.7$, $p < 0.001$, $\eta^2_p = 0.065$. In addition, ANCOVA led to a significant interaction of condition x group, $F(1.81, 488) = 5.97$, $p = 0.004$, $\eta^2_p = 0.022$. The interaction effect showed that the difference

TABLE 2 Participant characteristics of the LP-SP and HP-SP.

	LP-SP (*n* = 133)	HP-SP (*n* = 142)	Statistical analysis
Age (years)	18.7 (5.31)	16.5 (4.75)	$t(273) = 3.49$, $p = 0.001$, $d = 0.422$
Sex	112 male, 21 female	122 male, 20 female	$CHI^2(1) = 0.16$, $p = 0.692$
BMI (kg/m^2)	21.8 (3.03)	20.4 (2.75)	$t(250) = 3.97$, $p < 0.001$, $d = 0.502$
How old were you when you started regular training? (years)	8.61 (3.34)	5.95 (2.06)	$t(169) = 6.91$, $p < 0.001$, $d = 1.063$
Amount of training in soccer (min/week); freq. of naming soccer (n)	202 (83.9) *n* = 84	330 (70.9) *n* = 110	$t(215) = -12.12$, $p < 0.001$, $d = -1.653$
TMT-M; motor task (s)	9.31 (2.42)	7.66 (2.60)	$t(135) = 3.85$, $p < 0.001$, $d = 0.663$
TMT-A; numbers (s)	22.0 (7.63)	18.4 (6.11)	$t(135) = 3.07$, $p = 0.003$, $d = 0.528$
TMT-B; numbers& letters (s)	46.9 (13.8)	46.1 (15.8)	$t(135) = 0.334$, $p = 0.739$, $d = 0.057$

Mean values and standard deviations as well as statistical parameters, are given. HP-SP, high-performance soccer players; LP-SP, low-performance soccer players; BMI (Body Mass Index), Weight (in kilograms) / (Height (in meters) * Height (in meters)); TMT-M, Trail-Making Test – pure motor task; TMT-A, Trail-Making Test – numbers; TMT-B, Trail-Making Test – numbers & letters; s, seconds; n, frequency; $p < 0.05$, significant; $p < 0.01$; strongly significant; $p < 0.001$, highly significant; d, Cohens d.

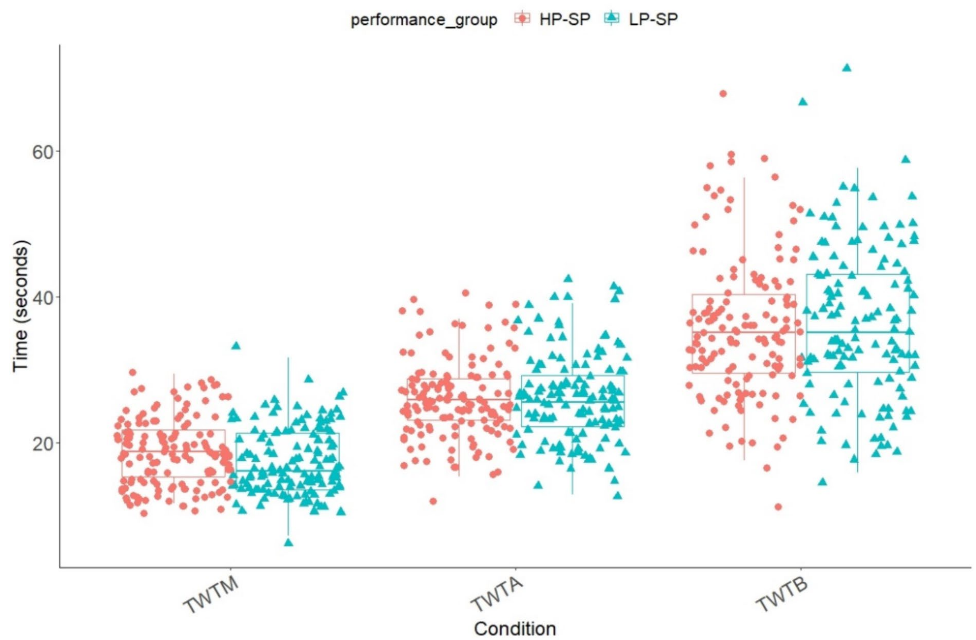


FIGURE 2
Means and standard deviation of groups and conditions in the TWT (TWT-M, TWT-A & TWT-B) based on the times. TWT-M, Trail-Walking Test – pure motor task; TWT-A, Trail-Walking Test – numbers; TWT-B, Trail-Walking Test – numbers & letters.

between the two performance groups becomes more pronounced with increasing difficulty. Also, significantly longer durations were observed in conditions with increased cognitive load. An interaction effect condition x age could also be reported $F(1.81, 488) = 19.1$, $p < 0.001$, $\eta^2_p = 0.066$. The post-hoc analysis showed that the durations in TDT-B ($M = 40.8$, $SE = 0.539$) were significantly higher than in TDT-A ($M = 33.3$, $SE = 0.406$) or the motor (TDT-M) condition ($M = 24.7$, $SE = 0.290$) ($p < 0.001$). Also, the *post hoc* analysis showed that in the TDT-M, $t(273) = 2.13$, $p = 0.035$, $d = 0.257$, the TDT-A, $t(270) = 3.44$, $p = 0.001$, $d = 1.55$ and the TDT-B, $t(272) = 5.15$, $p < 0.001$, $d = 1.44$, both groups differed significantly from each other, the HP group always outperformed the LP group.

3.3 Motor-cognitive interferences in the non-soccer-specific task (TWT) and the soccer-specific task (TDT)

3.3.1 Trail-walking test

Regarding the proportional DTC in the non-soccer specific task (TWT), a 2 (group: HP-SP vs. LP-SP) x 2 (condition: high vs. low cognitive load) x 2 (domain: cognitive vs. motor) ANCOVA with repeated measurements and age as covariates were calculated. The results showed a significant main effect domain, $F(1, 270) = 31.9$, $p < 0.001$ $\eta^2_p = 0.106$, with greater interference for the motor task (motor: $M = -79.5$, $SE = 2.44$; cognitive: $M = -45.5$, $SE = 2.87$) ($p < 0.001$). A significant interaction effect could be observed for

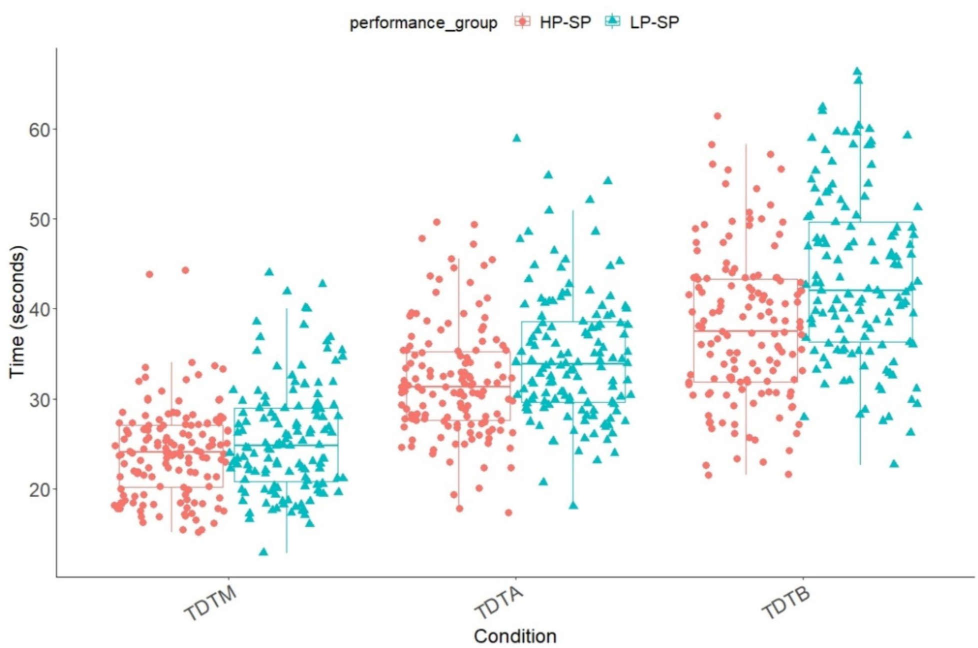


FIGURE 3
Means and standard deviation of the groups and conditions of the TDT (TDT-M, TDT-A & TDT-B) based on the times. TDT-M, Trail-Dribbling Test – pure motor task; TDT-A, Trail-Dribbling Test – numbers; TDT-B, Trail-Dribbling Test – numbers & letters.

domain x age, $F(1, 270) = 71.5$, $p < 0.001$, $\eta^2_p = 0.209$, as well as for condition x age, $F(1, 270) = 4.08$, $p = 0.044$, $\eta^2_p = 0.015$, and domain x condition, $F(1, 270) = 67.1$, $p < 0.001$, $\eta^2_p = 0.199$. Under low cognitive load, comparable motor and cognitive DTC were observed (motor: $M = -51.1$, $SE = 2.15$; cognitive: $M = -59.2$, $SE = 3.67$). With increased cognitive load, motor DTC was higher (motor: $M = -107$, $SE = 3.34$; cognitive: $M = -31.9$, SE = 3.08). The Pearson correlation coefficient for the relationship between age and motor or cognitive DTC showed that motor DTC increases with age (TWT-A: $r = -506$, $p < 0.001$; TWT-B: $r = -0.384$, $p < 0.001$) and cognitive DTC became less apparent with increasing age (TWT-A: $r = 0.268$, $p < 0.001$; TWT-B: $r = 0.136$, $p < 0.024$). A significant group difference in DTC in the non-soccer-specific task could not be observed (see Figure 4).

3.3.2 Trail-dribbling test

Regarding the proportional DTC in the soccer-specific task (TDT), a 2 (group: HP-SP vs.- LP-SP) x 2 (load: high vs. low cognitive load) x 2 (domain: cognitive vs. motor) ANCOVA with repeated measurements and age as covariates were calculated. The results showed a significant main effect domain, $F(1, 270) = 4.35$, $p = 0.038$ $\eta^2_p = 0.016$, with greater DTCs for the cognitive task (motor: $M = -53.4$, $SE = 1.87$; cognitive: $M = -190$, $SE = 9.49$) ($p < 0.001$). A significant interaction effect could be observed for domain x age, $F(1, 270) = 4.24$, $p = 0.040$, $\eta^2_p = 0.015$, as well as for condition x age, $F(1, 270) = 17.9$, $p < 0.001$, $\eta^2_p = 0.062$, and domain x load, $F(1, 270) = 19.6$, $p < 0.001$, $\eta^2_p = 0.068$. Both motor (TDT-A: $M = -38.1$, $SE = 1.74$; TDT-B: $M = -68.7$, $SE = 2.38$) and cognitive (TDT-A: $M = -178$, $SE = 8.23$; TDT-B: $M = -201$, $SE = 11.6$) DTCs were greater under increased cognitive load. The Pearson correlation coefficient for the relationship between age and motor or cognitive DTC showed that motor (TDT-A: $r = -468$, $p < 0.001$; TWT-B: $r = -0.435$, $p < 0.001$) and cognitive (TDT-A: $r = -0.149$, $p = 0.014$; TDT-B: $r = -0.261$, $p < 0.001$) DTCs increased with age. A significant difference in the DTC between groups in the soccer-specific task could not be observed (see Figure 5).

The following correlations emerged between the calculated pure cognitive performances and performances in the pure cognitive signaling tasks: [TWTA-TWTM] to signaling task: $r = 0.446$, $p < 0.001$; [TWTB-TWTM] to signaling task: $r = 0.367$, $p < 0.001$; [TDTA-TDTM] to signaling task: $r = 0.340$, $p = 0.001$; [TDTB-TDTM] to signaling task: $r = 0.374$, $p = 0.001$. Also, in the calculation of the cognitive DTCs, we observe strong correlations between both approaches: cDTC in TWTA: $r = 0.263$, $p < 0.001$; cDTC in TDTA: $r = 0.181$ $p = 0.015$; cDTC in TDTB: $r = 0.178$, $p = 0.015$. We do not see any significant correlation for cDTC in TWTB: $r = 0.063$, $p < 0.217$ (Figure 6).

3.4 ROC – analyses for the durations in the TDT

The TDT was beneficial in distinguishing HP-SP from LP-SP in the age groups between 14 and 15 years (AUC = 0.712–0.820) and between 16 and 17 years (AUC = 0.634–0.839) (Table 3).

4 Discussion

4.1 Behavioral results

The study's main objective was to introduce a method for quantifying motor-cognitive soccer-specific dribbling tasks and establish a theoretical foundation for this quantification. Specifically,

FIGURE 4
Means and standard deviation of the motor and cognitive DTC in the TWT (TWT-A, TWT-B) divided into high- and low-performance groups. TWT-M, Trail-Walking Test – pure motor task; TWT-A, Trail-Walking Test – numbers; TWT-B, Trail-Walking Test – numbers & letters.

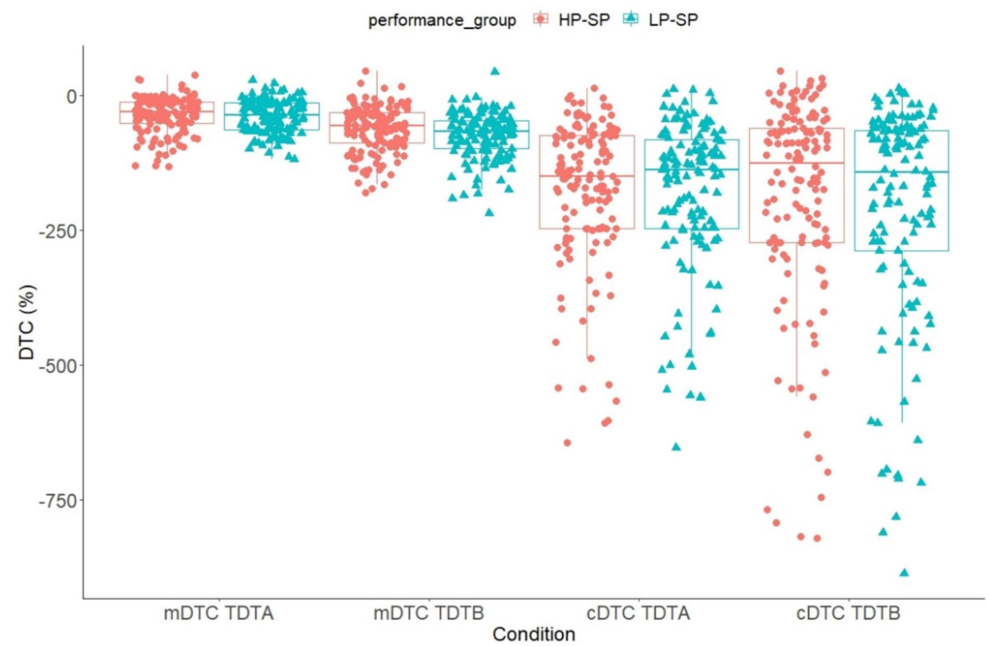


FIGURE 5
Means and standard deviation of the motor and cognitive DTC in the TDT (TDT-A, TDT-B) divided into the high- and low-performance groups. TDT-M, Trail-Dribbling Test – pure motor task; TDT-A, Trail-Dribbling Test – numbers; TDT-B, Trail-Dribbling Test – numbers & letters.

this method falls within the framework of the navigation DT paradigm, where a motor task (locomotion: here dribbling) and a cognitive task (wayfinding) (adapted from the Trail-Walking-Test, Schott, 2015) are combined and integrated into a large-scale spatial ability task.

Soccer, being an "open" sports game, presents unique challenges to players, requiring simultaneous engagement in both motor and cognitive tasks in almost all situations (Smith and Chamberlin, 1992; Gabbett et al., 2011; Scharfen and Memmert, 2019; Ren et al., 2022). Similar demands exist in other sports, where the ability to perform

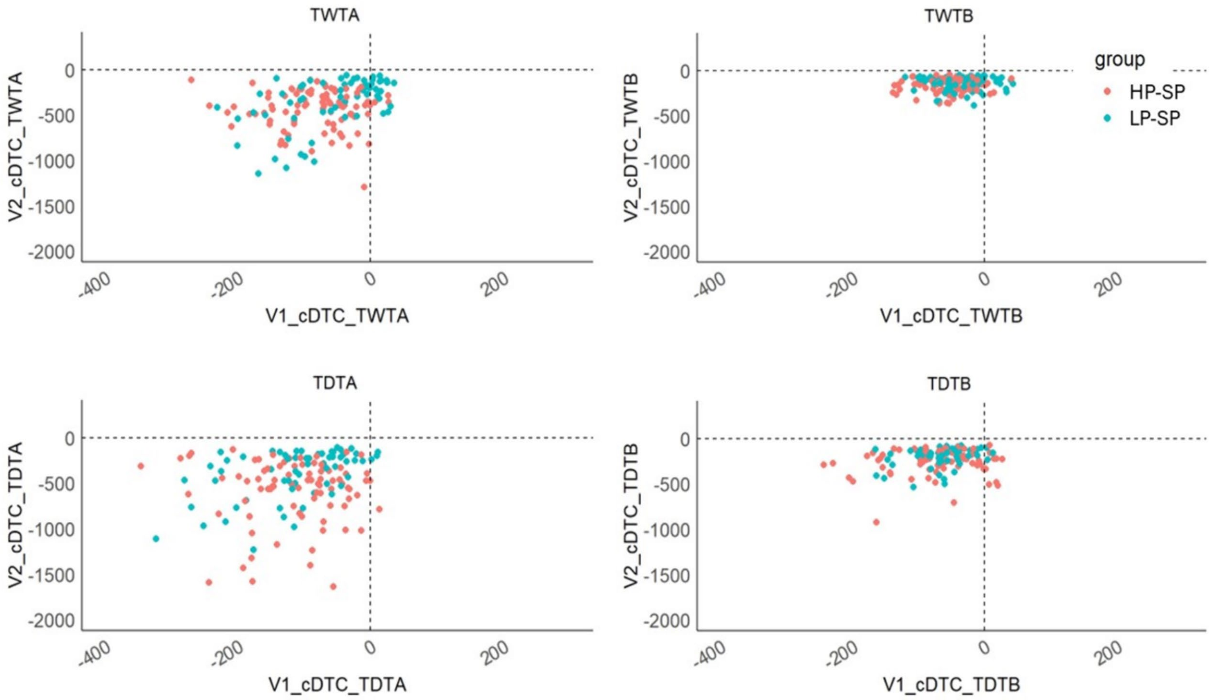


FIGURE 6
Scatter plot comparing the calculation methods for cognitive DTC under TWT and TDT conditions. V1, Calculation of DTCs based on cognitive performance with the signaling task; V2, Calculation of the DTCs based on cognitive performance with the formula (DT – motor ST); cDTC, cognitive dual-task costs; TWT, Trail-Walking Test; TDT, Trail-Dribbling Test; HP-SP, high performance soccer players; LP-SP, low performance soccer players.

TABLE 3 **Statistics and thresholds of the receiver-operating-characteristic curves for the TDT (velocities in TDT) to differentiate between high- and low-performance players.**

	n	Youden index	Sensitivity	Specificity	AUC	Threshold value	*p* value
12–13 years							
TDT-M	26/55	0.320	0.585	0.731	0.659	26.8	**0.022**
TDT-A	26/55	0.206	0.283	0.923	0.590	27.5	0.198
TDT-B	26/55	0.338	0.415	0.923	0.660	33.9	**0.021**
14–15 years							
TDT-M	15/27	0.781	0.929	0.852	**0.712**	23.6	**0.028**
TDT-A	15/27	0.526	0.786	0.741	**0.743**	28.8	**0.011**
TDT-B	15/27	0.677	0.714	0.963	**0.820**	38.5	**0.001**
16–17 years							
TDT-M	9/31	0.649	0.871	0.778	**0.839**	28.3	**0.002**
TDT-A	9/31	0.323	0.323	1.00	0.634	29.5	0.225
TDT-B	9/31	0.631	0.742	0.889	**0.817**	44.1	**0.004**
18–24 years							
TDT-M	31/56	0.388	0.548	0.839	0.657	18.5	**0.016**
TDT-A	31/56	0.140	0.195	0.946	0.513	24.8	0.842
TDT-B	31/56	0.222	0.258	0.964	0.597	27.6	0.136
25–34 years							
TDT-M	15/10	0.367	0.700	0.667	0.687	19.1	0.120
TDT-A	15/10	0.376	0.700	0.667	0.660	31.6	0.183
TDT-B	15/10	0.300	0.900	0.400	0.633	45.7	0.267

Significant results are shown in bold type; n = HP/LP. TDT-M, Trail-Dribbling Test – pure motor task; TDT-A, Trail-Dribbling Test – numbers; TDT-B, Trail-Dribbling Test – numbers & letters.

two tasks concurrently is essential for achieving a solid level of performance. However, this requirement becomes problematic when simultaneously processing different tasks, leading to a performance decrement in the single-task condition. For instance, beginners learning dribbling in basketball or soccer need to focus intensely on the ball, preventing them from observing the game (visual search), tracking the movements of their teammates and opponents, and making a decision about where to "go" next (wayfinding). Dribbling becomes increasingly synchronized and automated with training and practice, allowing players to "clear their heads" to process a second task (Carr et al., 2013). However, reliable guidelines on reaching this state of automation are scarce in relevant training manuals, and empirical evidence supporting such recommendations is usually lacking (Blischke and Reiter, 2002). The underlying concept in studies on cognitive-motor dual tasking is that resources are limited (e.g., Kahneman, 1973; Wickens, 2008), and performance tends to suffer when divided between a cognitive and a motor task. Resource competition is particularly evident in individuals who are in the process of acquiring a new motor skill (Schaefer, 2014). On the other hand, there seem to be certain situations where performing two tasks simultaneously can enhance motor and/or cognitive learning (for an overview, see Wollesen et al., 2022). However, the mechanisms underlying this interaction are not yet fully understood, making reliable predictions about the effects of different DT combinations challenging.

A further objective of this study was to compare the processing times of the Trail-Walking Test (TWT) and Trail-Dribbling Test (TDT) between high-performance soccer players (HP-SP) and low-performance soccer players (LP-SP) and to identify any performance advantages of HP-SP. In this respect, our first hypothesis can be confirmed, indicating that depending on the specificity of the task and the level of cognitive demand, interference effects, and group differences become more pronounced. It is worth noting that in both tasks (TWT and TDT) and across both performance groups, the processing durations increase as the cognitive load intensifies, consistent with numerous studies utilizing the DT paradigm in various domains (Schaefer, 2014). In the TWT, specifically the motor tracking task (TWT-M) without soccer-specific dribbling, there is only a small difference between HP-SP and LP-SP. The superior agility and motor speed of the HP-SP are among the factors that may explain this observation. In contrast, in the TDT, differences between the performance groups are evident in all conditions, with the disparities becoming more pronounced as the additional cognitive load increases. This finding aligns with the studies conducted by Smith and Chamberlin (1992), which also revealed more significant group differences between experts and novices under increased cognitive load. Similar patterns of larger differences in DT compared to ST conditions between experts and novices were observed in the study by Beilock et al. (2002).

Interferences predominantly occur in the cognitive domain, particularly under high cognitive load. Against our expectations, we found no differences in motor or cognitive performance declines between the HP-SP and LP-SP groups. In the TWT test, motor performance declines were greater than cognitive ones in both groups. However, in the TDT test, cognitive performance declines were higher than motor ones in all groups, no matter how difficult the additional task was. This observation is explained by the ability to focus on the cognitive task in the TWT while doing the more straightforward running task (without soccer-specific dribbling). Thus, both groups directed attentional resources toward the cognitive task, requiring only minimal cognitive resources for the running component. In the TDT, however, attention is primarily focused on the motor task, leading to neglect of the cognitive task. Presumably, players in both groups strongly prioritize attention toward the dribbled ball, which hampers visual search for numbers, numbers, and letters, resulting in higher DTC primarily in the cognitive task. On the other hand, this implies that participants have to update their next move constantly. Experts compared to lower-level soccer players are expected to flexibly switch and combine allocentric spatial processing skills [object-based or third-person perspective (relative to the environment)] and egocentric spatial processing, a navigational strategy based on a first-person perspective (relative to the body) because ball games with a high training and competition volume involve the use of this process more than in everyday life (Ekstrom et al., 2003). If they struggle to control the ball and follow a ball that goes the wrong way, they are more likely to "lose track" of the sequence of numbers and letters. In this sense, a lack of soccer-specific dribbling skills makes the 'in-built' cognitive task (wayfinding task) more challenging.

The second and third objectives were to evaluate the diagnostic quality of the Trail-Dribbling Test (TDT). Both performance groups were further divided into different age groups to achieve this, allowing for a more detailed assessment of the TDT's ability to differentiate between HP-SP and LP-SP. Our hypothesis can be confirmed, indicating that with increased cognitive demand, differentiation between HP-SP and LP-SP, especially in soccer-specific motor tasks, becomes evident. Between the ages of 14 and 15, the study demonstrated moderate (TWT-M: AUC = 0.712; TDT-A: AUC = 0.743) and good (TDT-B: AUC = 0.820) diagnostic quality in distinguishing between HP-SP and LP-SP. Moreover, as the additional cognitive load increased, the diagnostic quality of the TDT improved (TDT-M: AUC = 0.712, p = 0.013; TDT-A: AUC = 0.743, p = 0.008; TDT-B: AUC = 0.820, p = 0.001), with the TWT-B showing particularly good sensitivity (71.4%) and specificity (96.3%). Based on these results, it is appropriate to differentiate between the groups, especially using the TDT with high cognitive load (TWT-B), with a threshold value of 38.5 s for processing time. The diagnostic quality ranges from weak (TDT-A: AUC = 0.634) to good (TDT-M: AUC = 0.839; TDT-B: AUC = 0.817) between the ages of 16 and 17. Moderate cognitive load (TDT-M) only allows weak discrimination between HP-SP and LP-SP. Differentiation is most effective in motor soccer-specific dribbling tasks (TDT-M) and DTs with high cognitive load (TDT-B). This can be explained by the fact that for LP-SP, an additional simple cognitive task (TDT-A) leads to lower motor DTCs, possibly due to the automated and self-organized execution of the dribbling task. However, when cognitive load increases beyond a certain point, available resources become insufficient, resulting in significant impairments in LP-SP. This observation is consistent with the findings of Gabbett et al. (2011), who investigated the performance of skilled and lesser-skilled rugby players in a rugby drill under ST and DT conditions while simultaneously performing a verbal tone recognition task. The performance of experts was more resistant to skill decrement under DT conditions. As cognitive demands increase, competition for limited attention resources (Kahneman, 1973; Wickens, 2008) can have a negative impact that outweighs the benefits of an external focus of attention, ultimately leading to decreased performance (Constrained Action Hypothesis; Wulf et al., 2001). In motor tasks, directing attention to the task at hand may result in a performance loss, particularly for LP-SP. Poor diagnostic quality was observed in all other age groups (12–13; 18–24; 25–34 years) with AUC values ranging from 0.590 to 0.687. These results are consistent with the findings of Ljach and Witkowski (2010), who examined the development of coordination skills in 11- to 19-year-old soccer players ($n = 600$). They found that the period from 11 to 13 years was most conducive to the development of coordinative skills, followed by the period from 14 years onwards. This may explain why the discriminatory strength of the TDT is not observed until the age of 14 and may explain why there is no significant discrimination in the years between 12. The reliability of these measurements might have been improved by evaluating multiple trials for each condition. Additionally, the variation in participant numbers across different age groups may have influenced the statistical power of the results. Also, the threshold value for distinguishing performance groups was determined using the Youden Index. Alternatively, one could determine the desired sensitivity and evaluate the test's specificity. If the objective is to identify as many high-performing individuals as possible, a predetermined sensitivity value should be utilized. The test's specificity, which refers to its ability to identify low-performing individuals, can be considered secondary to the primary goal of talent identification. If a high percentage of players are falsely identified as test positive (false-positive) at low specificity, it may not have severe consequences as late-developing athletes may not be prematurely excluded.

4.2 Methodological suggestions

As Ali (2011) pointed out, research and practice often neglect the cognitive component when assessing skills and identifying talent. The cognitive component involves decision-making and information processing, which are a fundamental part of skill development. A motor-cognitive DT approach has been proposed to address this, aiming to integrate both domains. The DT method falls under the "Expert Performance Approach" (Mann et al., 2007) as it involves testing athletes under ecologically valid conditions using tasks such as visual search and cognitive flexibility that are representative of open sports like soccer. DT approaches allow for assessing skill automation (in this case, dribbling) and evaluating specific training methods to automate skills. Automation of skills is crucial since many skills practiced in training can break down under pressure or additional cognitive demands during real-game situations.

McIsaac et al. (2015) created a framework for a DT taxonomy to guide the discussion of existing evidence-based studies on interferences in DTs within a broader framework. This enables summative statements and leads to clarity and a better understanding of the research area. According to this classification scheme, tasks such as 'carrying a cup while walking' or 'talking on a mobile phone while walking' are not considered dual tasks (DTs). However, our perspective differs somewhat. We contend that in these scenarios, it is possible to entirely redirect our attentional resources from one activity (such as talking) to another (such as walking) despite the tasks not being entirely independent of each other. Therefore, we can also refer to a DT paradigm in our approach. McIsaac et al. (2015) classified tasks using a two-dimensional system that assesses 'Novelty' (familiarity with the task) and 'Task Complexity' (attention required, number of components, and degrees of freedom involved), ranging from 'High' to 'Low.' The level of attentional demand imposed by a secondary task may vary depending on the individual. For example, tasks that require mathematical skills may only require minimal mental effort if the individual is well-practiced in them. The same applies to soccer-specific experts and novices when it comes to soccer-specific motor tasks (TDT). As learning progresses, tasks can become more challenging by reducing the playing field, adding more numbers and letters, starting with different numbers with varying distances (e.g., 3–24-678) or different letters (e.g., C-E-G), or introducing a third feature (e.g., opponent figures with increasing size). Our approach aligns with McIsaac's taxonomy (refer to Table 4).

An alternative method for operationalizing cognitive performance in the TWT and TDT involves having the players stand in the center of the field and use a laser pointer to indicate numbers and letters (signaling task). This behavior is reminiscent of actions in soccer, where players signal running paths or provide specific positional instructions to their teammates. Simultaneously, this approach enhances the external validity of our procedure. Through this specific implementation of the cognitive task within the context of the TWT and TDT, ST cognitive performance can also be assessed. We applied this approach to a subset of our sample ($n = 165$) in addition to the aforementioned methods, and we identified strong correlations when comparing it to the calculated ST cognitive performance. This emphasizes the validity of operationalizing cognitive performance through signaling tasks or the calculation method used in our study as an effective approach for assessing cognitive performance in single tasks (STs) and calculating cognitive DTC.

Even though we did not conduct a longitudinal study that can confirm an effect over time, the TDT could potentially be used as a training tool to automate skills such as dribbling by incorporating an additional cognitive task. The difficulty level can be adjusted based on

TABLE 4 Exemplary integration of the TDT into the dual-task framework by McIsaac et al. (2015) for HP-SP (experts) and LP-SP (novices).

Group	Type of task	Task novelty	Task complexity	
HP-SP			Low	High
	Dual cognitive-motor	Low	TDT-A	TDT-B
		High		
Group	Type of task	Task novelty	Task complexity	
LP-SP			Low	High
	Dual cognitive-motor	Low		
		High	TDT-A	TDT-B

HP-SP, high-performance soccer players; LP-SP, low-performance soccer players; TDT-A, Trail-Dribbling Test with numbers; TDT-B, Trail-Dribbling Test with numbers & letters.

performance level by modifying the task, such as increasing the number of letters, starting at different numbers or letters (e.g., D-13-E-14), or extending the playing field. Variations such as dribbling the numbers and letters backward or dribbling letters corresponding to predefined terms/names are also possible variations. These variations aim to maintain high cognitive demands since the cognitive task of connecting numbers and letters in ascending order becomes easier or automated over time. Randomized changes in the stimuli can be introduced to maintain the visual search demands and enhance spatial orientation. These variations offer more motivation compared to the monotonous execution of the described TDT. Additionally, expanding the playing field accentuates different types of dribbling, such as "space-gaining" dribbling, requiring more considerable distances, particularly in larger playing fields. Conversely, smaller playing fields can emphasize "ball-keeping" dribbling. The selection of adjustments depends on specific requirements and training objectives, allowing for flexibility in the training approach.

5 Conclusion, limitations, and future directions

The study's results offer a new perspective on navigation research in ball sports, specifically soccer. They demonstrate that spatial disorientation, along with limitations in dribbling performance, can be effectively induced and evaluated in adolescent soccer players through the Trail-Dribbling Test. This is evidenced by the significantly higher dual-task costs observed in the high cognitive load condition.

Therefore, the TDT could be a suitable screening and training instrument for individuals aged 14 to 17 years. It is capable of observing more significant differences between performance groups as cognitive load increases. However, it is important to note that the TDT has not been compared to any gold-standard screening tools. Furthermore, the usefulness of this approach may be restricted due to its narrow age range (based on the results of this study). In soccer, talent identification and selection often depend on subjective evaluations made by experienced coaches (Christensen, 2009). Most studies in this field focus primarily on physiological aspects (e.g., endurance and speed) and anthropometric characteristics (i.e., height and weight) of players (Murr et al., 2018). However, these approaches may inadvertently exclude late-maturing individuals. The authors recommend considering multiple physiological measures in addition to the mentioned anthropometric characteristics.

However, using only a few test procedures to make selection decisions for the future success of young athletes is highly unsatisfactory. A holistic approach to talent identification should encompass physical resources, physiological characteristics, motivational factors, social opportunities, family support, personality traits, and cognitive-volitional features of athletes. Unfortunately, many of these talent criteria often go unconsidered. Therefore, it is not recommended to create or support selection criteria or make probability statements about future success based solely on one test. Additionally, the term 'talent' has multiple interpretations, and there are no universally accepted criteria to define the concept. This highlights the existence of various approaches to examining talent. To develop athletes' talent to its fullest potential, researchers and coaches should prioritize maximizing the factors that contribute to their success. The TDT assesses both cognitive and motor skills, making it a valuable tool in this regard.

When categorizing athletes as high-performing or low-performing, it is important to note that athletes competing in the "Landesliga" may not necessarily be considered 'experts'. This distinction could potentially impact the interpretation of the results. While the study aimed to include participants with varying levels of performance, it is crucial to recognize that the definition of 'expertise' can vary depending on the context and sport being studied. In this context, including Landesliga athletes in a soccer-specific study could potentially bias the results, particularly if they are perceived as less experienced or competent than athletes at higher performance levels (Bundesliga). Future research should carefully consider participant selection and competence definition to avoid such biases. It is crucial to consider other relevant factors, such as experience, training intensity, or individual performance history when assessing performance, rather than relying solely on the competition level. Categorizing participants into high-performance (HP) and low-performance (LP) groups by calculating a score could provide a more detailed and precise classification. Future research could investigate the feasibility of integrating both league classification and a calculated score based on relevant performance variables. This integration could lead to a more comprehensive and nuanced understanding of participants' performance levels, increasing the validity and depth of the results. This strategy requires careful consideration of the weighting and selection of performance variables to ensure that the derived scores accurately reflect athletes' abilities while remaining practical and interpretable.

Moving forward, a more comprehensive approach to talent identification and development in sports is necessary. Researchers and coaches should focus on maximizing athletes' potential by optimizing various factors, including cognitive and motor aspects. Further integration of non-traditional talent criteria, such as motivational factors, social support, and personality traits, could help create a more holistic picture of talents. Future research approaches could involve refining and adapting motor-cognitive decision-making tasks. By utilizing different variations and tasks in the decision-making process, athletes' flexibility and adaptability could be further enhanced. Integrating modern technologies, such as virtual reality, could offer new opportunities for training and assessing cognitive and motor skills. Future studies and practices in talent identification and development in sports should encompass a broader range of factors and criteria to gain a more comprehensive understanding of talents and ensure that no potential goes unnoticed. This approach can facilitate the optimal development and nurturing of athletes to help them achieve their full potential.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Commission for Responsibility in Research (Ethics Committee) of the University of Stuttgart. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

TJK: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. NS: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

We want to thank all study participants, the legal guardians of the children, and the organizations with which we collaborated.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Aberg, M. A., Pedersen, N. L., Torén, K., Svartengren, M., Bäckstrand, B., Johnsson, T., et al. (2009). Cardiovascular fitness is associated with cognition in young adulthood. *Proc. Natl. Acad. Sci.* 106, 20906–20911. doi: 10.1073/pnas.0905307106

Ali, A. (2011). Measuring soccer skill performance: a review. *Scand. J. Med. Sci. Sports* 21, 170–183. doi: 10.1111/j.1600-0838.2010.01256.x

Audiffren, M., and André, N. (2019). The exercise–cognition relationship: a virtuous circle. *J. Sport Health Sci.* 8, 339–347. doi: 10.1016/j.jshs.2019.03.001

Bartseva, K., Likhanov, M., Tsigeman, E., Alenina, E., Reznichenko, I., Soldatova, E., et al. (2024). No spatial advantage in adolescent hockey players? Exploring measure specificity and masked effects. *Intelligence* 102:101805. doi: 10.1016/j.intell.2023.101805

Beavan, A., Chin, V., Ryan, L. M., Spielmann, J., Mayer, J., Skorski, S., et al. (2020a). A longitudinal analysis of the executive functions in high-level soccer players. *J. Sport Exerc. Psychol.* 42, 349–357. doi: 10.1123/jsep.2019-0312

Beavan, A., Spielmann, J., Mayer, J., Skorski, S., Meyer, T., and Fransen, J. (2020b). The rise and fall of executive functions in high-level football players. *Psychol. Sport Exerc.* 49:101677. doi: 10.1016/j.psychsport.2020.101677

Beilock, S. L., Carr, T. H., MacMahon, C., and Starkes, J. L. (2002). When paying attention becomes coun-terproductive: impact of divided versus skill-focused attention on novice and experienced per-formance of sensorimotor skills. *J. Exp. Psychol. Appl.* 8, 6–16. doi: 10.1037/1076-898X.8.1.6

Blischke, K., and Reiter, C. (2002). Bewegungsautomatisierung durch Doppeltätigkeits-Üben. *Spectrum der Sportwissenschaften*.14:8–29. doi: 10.1007/s40279-017-0851-7

Brunyé, T. T., Gardony, A. L., Holmes, A., and Taylor, H. A. (2018). Spatial decision dynamics during wayfinding: intersections prompt the decision-making process. *Cogn. Res.* 3, 1–19. doi: 10.1186/s41235-018-0098-3

Brysbaert, M. (2019). How many participants do we have to include in properly powered experiments? A tutorial of power analysis with reference tables. *J. Cogn.* 2:16. doi: 10.5334/joc.72

Caldwell, A., and Lakens, D. (2019). Power analysis with superpower. Self Published on GitHub. Available at: https://aaroncaldwell.us/SuperpowerBook/ (Accessed Januar 29, 2024)

Campos, W. (1993). *The effects of age and skill level on motor and cognitive components of soccer performance*. Unpublished doctoral disseration. Pittsburgh: University of Pittsburgh.

Carling, C., Williams, M. A., and Reilly, T. (2007). *Handbook of soccer match analysis*. London: Routledge.

Carr, B. M., Etnier, J. L., and Fisher, K. M. (2013). Examining the time course of attention in a soccer kick using a dual task paradigm. *Hum. Mov. Sci.* 32, 240–248. doi: 10.1016/j.humov.2012.12.006

Casanova, F., Oliveira, J., Williams, M., and Garganta, J. (2009). Expertise and perceptual-cognitive performance in soccer: a review. *Revista Portuguesa de Ciências do Desporto* 9, 115–122. doi: 10.5628/rpcd.09.01.115

Christensen, M. K. (2009). "An eye for talent": talent identification and the "practical sense" of top-level soccer coaches. *Sociol. Sport J.* 26, 365–382. doi: 10.1123/ssj.26.3.365

Ekstrom, A. D., Kahana, M. J., Caplan, J. B., Fields, T. A., Isham, E. A., Newman, E. L., et al. (2003). Cellular networks underlying human spatial navigation. *Nature* 425, 184–188. doi: 10.1038/nature01964

Faul, F., Erdfelder, E., Lang, A. G., and Buchner, A. (2007). G* power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* 39, 175–191. doi: 10.3758/BF03193146

Gabbett, T., Wake, M., and Abernethy, B. (2011). Use of dual-task methodology for skill assessment and development: examples from rugby league. *J. Sports Sci.* 29, 7–18. doi: 10.1080/02640414.2010.514280

Gaudino, E. A., Geisler, M. W., and Squires, N. K. (1995). Construct validity in the trail making test: what makes Part B harder? *J. Clin. Exp. Neuropsychol.* 17, 529–535. doi: 10.1080/01688639508405143

Hilden, J., and Glasziou, P. (1996). Regret graphs, diagnostic uncertainty and Youden\u0027s Index. *Statistics in medicine*, 15, 969–986.

Imai, T., Moore, S. T., Raphan, T., and Cohen, B. (2001). Interaction of the body, head, and eyes during walking and turning. *Exp. Brain Res.* 136, 1–18. doi: 10.1007/s002210000533

Kahneman, D. (1973). *Attention and effort*, vol. *1063*. Englewood Cliffs, NJ: Prentice-Hall, 218–226.

Kannekens, R., Elferink-Gemser, M. T., and Visscher, C. (2011). Positioning and deciding: key factors for talent development in soccer. *Scand. J. Med. Sci. Sports* 21, 846–852. doi: 10.1111/j.1600-0838.2010.01104.x

Kiesel, A., Johannsen, L., Müller, H., and Koch, I. (2022). *Handbook of human multitasking*. Heidelberg Germany: Springer Nature.

Klotzbier, T. J., Bühler, K., Holfelder, B., and Schott, N. (2020). Exploring motor-cognitive interference in children with down syndrome using the trail-walking-test. *Res. Dev. Disabil.* 106:103769. doi: 10.1016/j.ridd.2020.103769

Knöbel, S., and Lautenbach, F. (2023). An assist for cognitive diagnostics in soccer (part II): development and validation of a task to measure working memory in a soccer-specific setting. *Front. Psychol.* 13:1026017. doi: 10.3389/fpsyg.2022.1026017

Koch, I., Poljac, E., Müller, H., and Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking - an integrative review of dual-task and task-switching research. *Psychol. Bull.* 144, 557–583. doi: 10.1037/bul0000144

Künzell, S., Bröker, L., Dignath, D., Ewolds, H., Raab, M., and Thomaschke, R. (2018). What is a task? An ideomotor perspective. *Psychol. Res.* 82, 4–11. doi: 10.1007/s00426-017-0942-y

Ljach, W. I., and Witkowski, Z. (2010). Development and training of coordination skills in 11-to 19-year-old soccer players. *Hum. Physiol.* 36, 64–71. doi: 10.1134/S0362119710010081

Mann, D. T., Williams, A. M., Ward, P., and Janelle, C. M. (2007). Perceptual-cognitive expertise in sport: a meta-analysis. *J. Sport Exerc. Psychol.* 29, 457–478. doi: 10.1123/jsep.29.4.457

McIsaac, T. L., Lamberg, E. M., and Muratori, L. M. (2015). Building a framework for a dual task taxonomy. BioMed research international, *2015*.

Montello, D. R. (2005). "Navigation" in *The Cambridge handbook of visuospatial thinking*. eds. A. Miyake and P. Shah. Cambridge England: (Cambridge University Press), 257–294.

Montello, D. R., and Sas, C. (2006). "Human factors of wayfinding in navigation" in *International encyclopedia of ergonomics and human factors*. ed. W. Karwowski. *2nd* ed (London England: CRC Press/Taylor & Francis Ltd), 2003–2008.

Moreira, P. E. D., Dieguez, G. T. O., Bredt, S. D. G. T., and Praça, G. M. (2021). The acute and chronic effects of dual-task on the motor and cognitive performances in athletes: a systematic review. *Int. J. Environ. Res. Public Health* 18:1732. doi: 10.3390/ijerph18041732

Murr, D., Feichtinger, P., Larkin, P., O'Connor, D., and Höner, O. (2018). Psychological talent predictors in youth soccer: a systematic review of the prognostic relevance of psychomotor, perceptual-cognitive and personality-related factors. *PLoS One* 13:e0205337. doi: 10.1371/journal.pone.0205337

Murr, D., Raabe, J., and Höner, O. (2018). The prognostic value of physiological and physical characteristics in youth soccer: a systematic review. *Eur. J. Sport Sci.* 18, 62–74. doi: 10.1080/17461391.2017.1386719

Musculus, L., Lautenbach, F., Knöbel, S., Reinhard, M. L., Weigel, P., Gatzmaga, N., et al. (2022). An assist for cognitive diagnostics in soccer: two valid tasks measuring inhibition and cognitive flexibility in a soccer-specific setting with a soccer-specific motor response. *Front. Psychol.* 13:1332. doi: 10.3389/fpsyg.2022.867849

Nuri, L., Shadmehr, A., Ghotbi, N., and Attarbashi Moghadam, B. (2013). Reaction time and anticipatory skill of athletes in open and closed skill-dominated sport. *Eur. J. Sport Sci.* 13, 431–436. doi: 10.1080/17461391.2012.738712

Padulo, J., Chamari, K., and Ardigò, L. P. (2014). Walking and running on treadmill: the standard criteria for kinematics studies. *Muscles Ligaments Tendons J.* 4, 159–162. doi: 10.32098/mltj.02.2014.13

Plummer, P., and Eskes, G. (2015). Measuring treatment effects on dual-task performance: a framework for research and clinical practice. *Front. Hum. Neurosci.* 9:225. doi: 10.3389/fnhum.2015.00225

Reitan, R. M. (1958). Validity of the trail making test as an indicator of organic brain damage. *Percept. Mot. Skills* 8, 271–276. doi: 10.2466/pms.1958.8.3.271

Ren, Y., Wang, C., and Lu, A. (2022). Effects of perceptual-cognitive tasks on inter-joint coordination of soccer players and ordinary college students. *Front. Psychol.* 13:892118. doi: 10.3389/fpsyg.2022.892118

Roca, A., Ford, P. R., McRobert, A. P., and Mark Williams, A. (2011). Identifying the processes underpinning anticipation and decision-making in a dynamic time-constrained task. *Cogn. Process.* 12, 301–310. doi: 10.1007/s10339-011-0392-1

Sakamoto, S., Takeuchi, H., Ihara, N., Ligao, B., and Suzukawa, K. (2018). Possible requirement of executive functions for high performance in soccer. *PLoS One* 13:e0201871. doi: 10.1371/journal.pone.0201871

Salthouse, T. A. (2011). What cognitive abilities are involved in trail-making performance?. *Intelligence*, 39, 222–232.

Salvucci, D. D., and Taatgen, N. A. (2011).Toward a unified view of cognitive control. *Topics in cognitive science*: Oxford University Press. 3, 227–330.

Sarmento, H., Anguera, M. T., Pereira, A., and Araújo, D. (2018). Talent identification and development in male football: a systematic review. *Sports Med.* 48, 907–931. doi: 10.1007/s40279-017-0851-7

Schaefer, S. (2014). The ecological approach to cognitive–motor dual-tasking: findings on the effects of expertise and age. *Front. Psychol.* 5:1167. doi: 10.3389/fpsyg.2014.01167

Scharfen, H. E., and Memmert, D. (2019). The relationship between cognitive functions and sport-specific motor skills in elite youth soccer players. *Front. Psychol.* 10:817. doi: 10.3389/fpsyg.2019.00817

Schott, N. (2015). Trail walking test for assessment of motor cognitive interference in older adults: development and evaluation of the psychometric properties of the procedure. *Z. Gerontol. Geriatr.* 48, 722–733. doi: 10.1007/s00391-015-0866-3

Schott, N., El-Rajab, I., and Klotzbier, T. (2016). Cognitive-motor interference during fine and gross motor tasks in children with developmental coordination disorder (DCD). *Res. Dev. Disabil.* 57, 136–148. doi: 10.1016/j.ridd.2016.07.003

Smith, M. D., and Chamberlin, C. J. (1992). Effect of adding cognitively demanding tasks on soccer skill performance. *Percept. Mot. Skills* 75, 955–961. doi: 10.2466/pms.1992.75.3.955

Strayer, D. L., Castro, S. C., and McDonnell, A. S. (2022). "The multitasking motorist" in *The handbook of human multitasking*. eds. A. Kiesel, L. Johannsen, H. Müller and I. Hoch (Berlin Deutschland: Springer).

Swann, C., Moran, A., and Piggott, D. (2015). Defining elite athletes: issues in the study of expert performance in sport psychology. *Psychol. Sport Exerc.* 16, 3–14. doi: 10.1016/j.psychsport.2014.07.004

Tabachnick, B. G., Fidell, L. S., and Ullman, J. B. (2013). *Using multivariate statistics*, vol. *6*. Boston, MA: Pearson, 497–516.

Wickens, C. D. (2008). Multiple resources and mental workload. *Hum. Factors* 50, 449–455. doi: 10.1518/001872008X288394

Wiener, J. M., Büchner, S. J., and Hölscher, C. (2009). Taxonomy of human wayfinding tasks: a knowledge-based approach. *Spat. Cogn. Comput.* 9, 152–165. doi: 10.1080/13875860902906496

Williams, A. M. (2000). Perceptual skill in soccer: implications for talent identification and development. *J. Sports Sci.* 18, 737–750. doi: 10.1080/02640410050120113

Williams, A. M., and Reilly, T. (2000). Talent identification and development in soccer. *J. Sports Sci.* 18, 657–667. doi: 10.1080/02640410050120041

Wollesen, B., Janssen, T. I., Müller, H., and Voelcker-Rehage, C. (2022). Effects of cognitive-motor dual task training on cognitive and physical performance in healthy children and adolescents: a scoping review. *Acta Psychol.* 224:103498. doi: 10.1016/j.actpsy.2022.103498

Woods, C. T., Rudd, J., Robertson, S., and Davids, K. (2020). Wayfinding: how ecological perspectives of navigating dynamic environments can enrich our understanding of the learner and the learning process in sport. *Sports Med.* 6:51. doi: 10.1186/s40798-020-00280-9

World Medical Association. Declaration of Helsinki, ethical principles for medical research involving human subjects. *64 nd WMA General Assembly*, Fortaleza, Brazil. (2013). Available at: https://www.wma.net/policies-post/wma-declarationof-helsinki-ethical-principles-for-medical-research-involving-human-subjects. (Accessed April 1, 2023).

Wulf, G., McNevin, N., and Shea, C. H. (2001). The automaticity of complex motor skill learning as a function of attentional focus. *Q. J. Exp. Psychol. Sec. A* 54, 1143–1154. doi: 10.1080/713756012

Yang, Y., Merrill, E. C., Robinson, T., and Wang, Q. (2018). The impact of moving entities on wayfinding performance. *J. Environ. Psychol.* 56, 20–29. doi: 10.1016/j.jenvp.2018.02.003

Frontiers in Psychology

TYPE Original Research
PUBLISHED 08 July 2024
DOI 10.3389/fpsyg.2024.1390536

Check for updates

OPEN ACCESS

EDITED BY
Kylie Ann Steel,
Western Sydney University, Australia

REVIEWED BY
Filipe Casanova,
Lusofona University, Portugal
Robert Rein,
German Sport University Cologne, Germany

*CORRESPONDENCE
Bruno Travassos
✉ bfrt@ubi.pt

RECEIVED 23 February 2024
ACCEPTED 24 June 2024
PUBLISHED 08 July 2024

CITATION
Rodrigues M, Leite N, Ribeiro JN, Sampaio J, Araújo D and Travassos B (2024) Understanding the visual search strategies of expert and novice coaches in futsal set pieces. *Front. Psychol.* 15:1390536.
doi: 10.3389/fpsyg.2024.1390536

Understanding the visual search strategies of expert and novice coaches in futsal set pieces

Manuel Rodrigues[1,2,3], Nuno Leite[1,2], João N. Ribeiro[4,5,6], Jaime Sampaio[1,2], Duarte Araújo[7] and Bruno Travassos[2,3,4]*

[1]Department of Sports Sciences, Exercise and Health, Universidade Trás-os-Montes e Alto Douro, Vila Real, Portugal, [2]Research Center in Sports Sciences, Health Sciences and Human Development, Centro de Investigação em Desporto, Saúde e Desenvolvimento Humano (CIDESD), CreativeLab Research Community, Vila Real, Portugal, [3]Portugal Football School, Federação Portuguesa de Futebol, Oeiras, Portugal, [4]Department of Sport Sciences, Universidade da Beira Interior, Covilhã, Portugal, [5]Polytechnic Institute of Guarda, School of Education, Communication and Sports, Guarda, Portugal, [6]SPRINT Sport Physical Activity and Health Research and Innovation Center, Viana do Castelo, Portugal, [7]Centro Interdisciplinar de Performance Humana – Organization (CIPER), Faculty of Human Motricity, Universidade de Lisboa, Cruz Quebrada, Portugal

Introduction: This study aimed to describe the fixation location and the time of the longer fixation of expert and novice futsal coaches before the ball was in play in futsal set pieces.

Methods: A total of 10 experts (ages 48 ± 5) and 10 novice coaches (ages 40 ± 7) participated in the study. They observed that 38 video clips were created to mimic the attack and defensive set-piece moments of the game. Data were collected in a standardized video analysis task using the pupil invisible eye tracker and processed through the pupil cloud platform. The Mann–Whitney test was conducted to evaluate differences in gaze duration between game moments (attack and defense set pieces) and groups (expert vs. novice). Gaze duration was also compared for gaze location between groups. For further comparisons, the game moments (attack and defense set pieces) and the gaze location were summarized in two-dimensional graphics using correspondence analysis.

Results and discussion: The results revealed higher values of gaze duration for attack and defense set pieces for the group of experts than for novices. When considering gaze duration, expert coaches had higher values than novices for the attacker 3, defender 3, barrier 1st, and barrier 2nd gaze locations. The correspondence analysis showed different strategies of visual search and, consequently, gaze locations for attack and defense set pieces. In particular, there was different correspondence for free kicks between the level of expertise and gaze location, while corner and sideline kicks revealed some correspondence between the groups and the gaze location. In free kicks, coaches should be particularly concerned about the relationship between attacker and defender three and the barrier 1st and 2nd line positions. In corner and sideline kicks, coaches should be particularly aware of the relationship between attackers' and defenders' positions.

KEYWORDS
expertise, visual perception, coaching, team sports, set pieces, decision-making

Introduction

Futsal, as a team sport, is characterized by its high level of unpredictability, based on constant alternations in the pace of play and possession of the ball. In this context, different game moments are characterized by specific game dynamics, forcing players and coaches to pick up different visual information to prospectively understand the best individual and collective possibilities for actions (Travassos et al., 2012; Rodrigues et al., 2024). For example, previous research reported differences in the visual search strategies and, consequently, in the visual information used by coaches to characterize the attack, defense, and set pieces in game moments (Rodrigues et al., 2024). In particular, the set pieces or "dead ball situations" (Hüttermann et al., 2018), game moments in which the ball is stationary, revealed specificities in the visual information used by futsal coaches in comparison with the regular attack or defense game moment (Rodrigues et al., 2024). Interestingly, the set pieces are a dangerous game moment in which the ball starts stationary, and there are movements of attackers and defenders before the ball is in play to open passing and shooting lines. Previous research showed that the set pieces in the game moment in futsal account for ∼25% of all shots made by a team during the game, and in the 2010 European futsal championship, the Portuguese team scored 46% of their goals with set pieces (Leite, 2012). The percentage of successful set pieces seems to be one of the variables that best distinguish winning teams from losing/drawing teams (Santos et al., 2020), requiring further attention from coaches for its preparation.

Within this scenario, since the visual information of the game is circumstantial to each game moment, the coach's knowledge and attunement to the relevant information (i.e., the capacity to perceive the relevant information according to each game moment) is paramount to shaping and guiding their behavior (Wood et al., 2023). In line with the ecological dynamics approach, the coaches' ability to understand game dynamics and support decision-making depends on their perceptual abilities to explore each game moment, extracting the most informational variables (Araújo et al., 2009). Thus, analyzing the coaches' visual search strategies in specific game moments can play an important role in further understanding how coaches explore the game to understand players' and teams' possibilities for action (Roca et al., 2011; Silva et al., 2013).

Mann et al. (2007) suggested that in sports, experts tend to capture relevant information from the environmental context with greater precision than novice coaches. The analysis of gaze behavior using variables, such as the number of fixations, their duration, and location (Lebeau et al., 2016), has sought to distinguish the visual search strategies of different levels of expertise among players and coaches. However, variables including the location of fixations and the quiet eye duration, i.e., the final fixation or tracking gaze at a specific location for a minimum of 100 ms, before movement initiation (Vickers, 2016), have emerged as variables that consistently distinguish experts from novices (Mann et al., 2007; Klostermann and Moeinirad, 2020). Previous research showed that a longer gaze fixation at specific locations and for an optimal amount of time prior to movement proves to be a characteristic of expert players (Vickers, 2016; Klostermann and Moeinirad, 2020). Although considering that coaches do not execute a motor skill in the same way as athletes, in futsal set pieces, it is paramount to understand the specific locations of the longer gaze fixation before the ball is in play to understand the information that supports the anticipation of set piece possibilities for an action (Hüttermann et al., 2018). In fact, the analysis of the information used before the ball is in play could help to understand the anticipation strategies followed by coaches and the sources of information that guide their decision-making (Mann et al., 2007).

To the best of our knowledge, no study with coaches has analyzed the visual search strategies, particularly the longer fixation at a particular location, before the ball is in play in set pieces. Thus, this study aimed to describe the fixation location and the time of the longer fixation of expert and novice futsal coaches before the ball is in play in futsal set pieces. It was hypothesized that expert coaches present longer fixations at different locations than novice coaches.

Methodology

Sample

A total of 10 expert (mean age 48 ± 5 years and years of experience 18 ± 4) and 10 novice (mean age 40 ± 7 years and years of experience 1 ± 1) futsal coaches participated in the study. The expert coaches had at least 10 years of experience, held Level III/IV futsal coaching certificates, and were serving as coaches of the national first division or national teams by the time of the research. All the coaches belonging to the expert group had won at least one national or international title. The group of novices completed the Futsal Level I coach course in Portugal in the year of data collection. This study was approved by the Ethics Committee of UTAD/CIDESD (UIDB/04045/2020). The participating coaches signed the free and informed consent form, authorizing the data collection and its use for research purposes, guaranteeing their anonymity.

Procedures

A total of 38 video clips were created to sample the attack and defensive set-piece moments of futsal. A total of 20 clips were attack set pieces (2 min of exposure): seven clips, offensive corner kicks (OfCor); seven clips, offensive sideline kicks (OfSide); six clips, offensive free kicks (OfFree) and 18 clips were defense set pieces (2 min of exposure): six clips, defensive corner kicks (DefCor); six clips, defensive sideline kicks (DefSid); and six clips, defensive free kicks (DefFree). The order of the clips for each game moment was kept constant, with the sequence of the three-game moment categories randomized across participants.

The technical footage and video clips were obtained from the Portuguese Football Federation and selected by convenience and consensus by the first and last authors (expert futsal coaches) to represent attack and defense set pieces (Roca et al., 2011). The videos were filmed from an elevated view of the field, which is a similar perspective to the videos that coaches usually use to analyze opponents. The overall videos were previously used by Portuguese Football Federation coaches for the same purpose. The participants were asked to watch the clips focusing on one of the teams, similar to how they would analyze an opponent's team. Before starting the video, they received specific instructions on whether to focus on the team's attacking or defensive play.

In this study, video clips were projected onto a screen (2.7 m × 3.6 m) using a projector (LG CineBeam LED HD 1,280 × 720) (Roca et al., 2011). The coaches were positioned two and a half meters away from the screen, allowing them to view the clips from a third-person perspective and an elevated view. When viewing the videos, all the participants used the Pupil Invisible eye-tracker system by Pupil Labs (120 Hz high-speed camera, 200 Hz eye camera), which has two built-in infrared cameras, one on each side. Infrared LEDs placed near the cameras located in the eye area were used to activate the lighting, enabling the Pupil invisible system to be used in dark environments (Tonsen et al., 2020). This setup was connected to a smartphone that recorded data relating to visual search strategies while watching the videos. The coaches were instructed to watch the video clips of the game to analyze the opponent: first by characterizing the scenes related to attack set pieces and then those related to defense set pieces. All the coaches went through a period of familiarization in which they watched all the videos one time and were given the opportunity to inquire about the data collection procedures.

Data collection

Data collection for set pieces in the analysis began the moment the ball was placed on the ground, and data collection was stopped the moment the ball started to move, leaving the foot of the set piece taker (Figure 1).

During the time in analysis, the longer fixation location, for a minimum of 100 ms of duration, and the location of the fixation were considered for analysis (Aksum et al., 2020; Casanova et al., 2022; Ballet et al., 2023). When two locations were superimposed during the fixation, both locations were registered. Thus, considering the object(s) inserted in the gaze circle, the following locations were included in the analysis (Figure 2): attacker without a ball (A), defender (D), space (S), attacker 2 (A2), attacker 3 (A3), attacker 4 (A4), defender 1 (D1), defender 2 (D2), defender 3 (D3), defender 4 (D4), set piece taker (SPT) barrier 1st line (B1) and barrier 2nd line (B2). The attackers and defenders were assigned 1–4 according to the initial distance to the ball, a strategy used by coaches to discriminate the positions of players in set pieces.

Statistical analysis

A Shapiro–Wilk test was used to assess the data distribution. Due to the existence of a non-normal distribution of data, the comparisons between performance variables were assessed using a non-parametric test. The Mann–Whitney test was conducted to assess general differences in gaze duration for attack and defense game moments between the two groups of coaches (expert vs. novice). We also compared the gaze duration, considering the gaze location between the groups. The significance level was set at a p-value of ≤ 0.05. To avoid Type I errors when comparing gaze duration considering the gaze location between expert and novice coaches, multiple testing using Bonferroni correction was made, and the significance level was set at a p-value of ≤ 0.004. The magnitude of differences was assessed using Hedges' g effect sizes (≥ 0.2–0.5 small, ≥ 0.5–0.08 moderate, and ≥ 0.8 large effect size). The game moments (attack and defense set pieces) and the gaze location were analyzed through correspondence analysis. This is a statistical technique similar to principal component analysis, in which the common position of the categories in the distance from the center of the presentation is to be interpreted as the correlation or correspondence of the categories. This technique allows for the analysis of simple two-way tables containing some measure of correspondence between the rows and columns. The data were summarized in two-dimensional graphics, allowing the visualization of the relationships between the categorical variables game moments and gaze location. Each row and column of the contingency table represents a variable and was represented as a point in the plot. The distance between points reflects the association between variables. Points that are closer together indicate stronger associations between the correspondent variables. The correspondence analysis, through the two-dimensional graphics, provides a visual summary of the data, making it easier to understand the complex relationship between the categories of variables. Each dimension in correspondence analysis corresponds to a principal component that explains the variance obtained (i.e., inertia). Two different plots were constructed to stratify the results according to the game moments (attack and defense set pieces) and gaze location in expert and novice groups. Statistical analyses were performed using SPSS 24.0 (SPSS Inc., Chicago, IL, United States).

Results

The analysis of the gaze duration for the attack (OfCor, OfSid, OfFree) and defense set pieces (DefCor, DefSid, DefSid) showed statistically significant differences between the groups, with moderate to large effect sizes for all the moments considered, with the exception of the defensive sideline, which revealed only a small effect. The higher values of gaze duration were observed for the group of experts than novices (Table 1). Interestingly, the group of experts revealed higher variability in gaze duration for most of the game moments than the group of novices (Table 1).

The analysis of gaze duration (ms), considering the location, showed statistically significant differences, with moderate to large effect sizes, between groups for the variables including attacker 3 (A3), defender 3 (D3), and barrier 1st line (B1st). Only the expert coaches used the information from barrier 2nd line (B2nd line) during the time of analysis. Higher values of gaze duration, considering location, were observed for the group of experts than for novices (Table 2). As previously observed, the group of experts revealed higher variability in gaze duration considering the location than the group of novices (Table 2).

Attack set pieces

The chi-square analysis for the attack set pieces showed a significant association between the group and gaze location ($X^2 = 483.04$, $p < 0.001$), justifying the use of correspondence analysis. The analysis of each dimension revealed that dimension 1 explained 64.4% of the variation, and dimension 2 explained 20.6% of the variation. In total, a cumulative 84.9% of the inertia is explained by the two dimensions created. The results revealed that dimension 1 was predominantly characterized by expert offensive free kicks (45.5% of inertia) and novice offensive free kicks (30.2% of inertia),

FIGURE 1
Representation of the moment the ball is placed on the ground until it leaves the performer's foot.

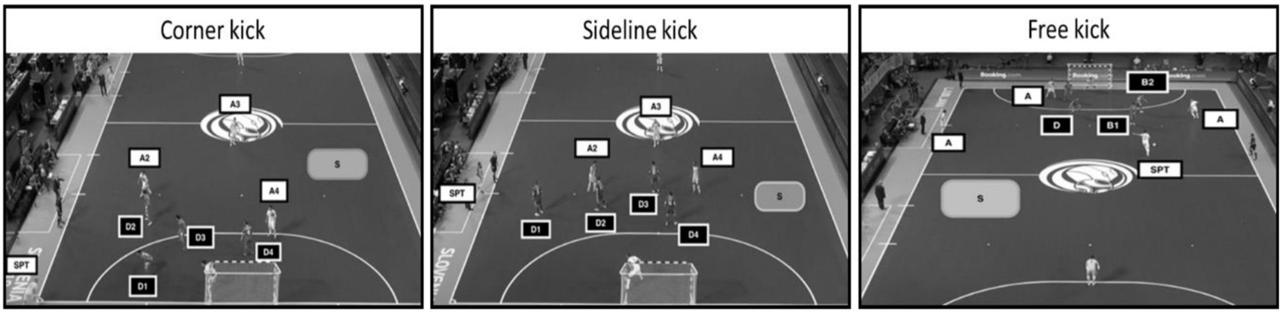


FIGURE 2
Representation of the variables included for the game moments attack and defense set pieces (free kick).

while dimension 2 was predominantly characterized by novice offensive free kicks (46.7% of inertia) and expert offensive free kicks (42.8% of inertia). Regarding the gaze location, the results revealed that dimension 1 was predominantly characterized by the attacker without the ball (A) (34.7% of inertia), the defender (D) (21.2% of inertia), the barrier 1st line (B1st) (13.4 of inertia), attacker 2 (A2) (8% of inertia), and attacker 3 (A3) (7% of inertia). Dimension 2 was predominantly characterized by the attacker without ball (A) (31.1% of inertia), defender (D) (28.7% of inertia), space (S) (13.8% of inertia), and barrier 1st line (B1st) (11% of inertia).

By examining the biplots of attacking set pieces (Figure 3), the expert and novice coaches were always represented in different quadrants for the same set piece moment, revealing a distinct relationship with gaze location variables, particularly explained by variations in dimension 2. While the analysis of offensive free kicks by experts (Exp-OfFree) is represented in the left lower panel, the analysis of offensive free kicks by novices (Nov–OfFree) is represented in the left upper panel. Accordingly, different associations were observed between gaze location variables. The offensive free kicks of experts (Exp-OfFree) revealed some correspondence with the gaze locations attacker without a ball (A) and barrier 1st line (B1), while the offensive free kicks of novices (Nov–OfFree) revealed some correspondence with the gaze locations defender (D), space (S), and set piece taker (SPT).

The analysis of the offensive corner and sideline of experts (Exp-OfCor and Exp-OfSid) is represented in the lower right panel, while the offensive corner and sideline of novices (Nov-OfCor and Nov-OfSid) are represented in the upper right corner. However, the distance between them was small, not allowing them to clearly distinguish the preferential information that is used by each one.

Defense set pieces

The chi-square analysis for the defense set pieces showed a significant association between the group and gaze location ($X^2 =$ 457,21, $p < 0.001$), justifying the use of correspondence analysis. The analysis of each dimension revealed that dimension 1 explained 61.2% of the variation, and dimension 2 explained 19.8% of the variation. In total, a cumulative 81.1% of the inertia is explained by the two dimensions created. The results revealed that dimension 1 was predominantly characterized by expert defense free kicks (55.7% of inertia) and novice defense free kicks (17.6% of inertia), while dimension 2 was characterized by novice defense free kicks (66.2% of inertia) and expert defense free kicks (25.4% of inertia). Regarding the gaze location, the results revealed that dimension 1 was predominantly characterized by an attacker without ball (A) (26.9% of inertia), defender (D) (21.9% of inertia), and barrier 1st line (21.3% of inertia). Dimension 2 was predominantly characterized by an attacker without a ball (A) (37.8% of inertia), a defender (27.7% of inertia), and a set-piece taker (SPT) (22.8% of inertia).

By examining the biplots of defensive set pieces (Figure 4), the expert and novice coaches were always positioned in different quadrants for the same set piece moment, revealing a distinct

TABLE 1 Gaze duration between expert and novice coaches for each attack and defense set piece.

	Gaze duration (ms)						
	Experts		Novices		*U*	*P*	*g*
	Median	IQR	Median	IQR			
Offensive corner kick	807.00	1,064.00	451.00	564.00	2,624.00	**0.001**	0.56
Offensive sideline kick	1,389.00	1,335.00	578.00	683.25	1,005.00	**0.001**	0.94
Offensive free kick	1,118.00	1,217.00	554.50	644.75	751.50	**0.010**	0.73
Defensive corner kick	1,034.00	800.75	463.00	573.00	818.00	**0.001**	0.74
Defensive sideline kick	1,007.00	1,377.50	664.00	836.00	775.50	**0.026**	0.41
Defensive free kick	1,380.00	1,606.75	791.00	808.50	538.50	**0.008**	0.79

IQR, interquartile range. The bold values indicate statistically significant differences.

TABLE 2 Gaze duration considering the gaze location between expert and novice coaches.

	Gaze duration (ms)						
	Experts		Novices		*U*	*P*	*g*
	Median	IQR	Median	IQR			
A	999.50	1,511.25	976.00	842.00	131.50	0.665	0.39
D	1,108.00	2,232.00	580.00	940.75	159.00	0.064	0.65
S	571.00	797.00	608.00	740.00	545.50	0.776	0.08
A2	1,104.00	1,283.00	640.00	666.50	783.00	0.011	0.57
A3	1,379.00	1,432.00	676.00	576.00	465.00	**0.001**	**0.77**
A4	1,028.00	979.00	892.00	1,924.00	180.00	0.698	0.03
D1	463.50	821.75	345.50	531.50	158.00	0.609	0.22
D2	1,063.00	1,026.00	715.00	542.25	264.50	0.008	0.61
D3	1,189.50	865.75	443.50	356.25	91.00	**0.001**	**1.31**
D4	1,079.00	1,279.00	735.00	689.50	178.00	0.136	0.49
SPT	815.00	1,097.00	308.00	317.00	138.00	0.009	1.11
B1st	1,417.50	1,279.50	369.50	414.00	27.00	**0.002**	**1.22**
B2nd	1,067.00	1,191.00	0	0	–	–	–

IQR, interquartile range. The bold values indicate statistically significant differences.

relationship with gaze location variables, particularly explained by variations in dimension 2. The analysis of defensive free kicks of experts (Exp-DefFree) is represented in the lower left panel, while novices (Nov–DefFree) appear in the upper left panel. Accordingly, different associations were observed with gaze location variables. The defensive free kicks by experts (Exp-DefFree) revealed some correspondence with the gaze locations attacker without a ball (A) and barrier 1st line (B1), while the defensive free kicks by novices (Nov–DefFree) revealed some correspondence with gaze locations defenders (D), barrier 2nd line (B2), space (S), and set piece takers (SPTs).

The analysis of the defensive corner and sideline of experts (Exp-DefCor and Exp-DefSid) is displayed in the lower right panel, while the defensive corner and sideline of novices (Nov-DefCor and Nov-OfSid) are shown in the upper right corner. However, the distance between them was small, hindering the clear differentiation of the preferential information that is used by each group.

Discussion

This study aimed to describe the fixation location and the time of the longer fixation of expert and novice futsal coaches before the ball was in play in futsal set pieces. The results partially confirm the hypothesis that expert coaches present longer fixations at different locations than novice coaches. The gaze duration presented significant differences between expert and novice coaches

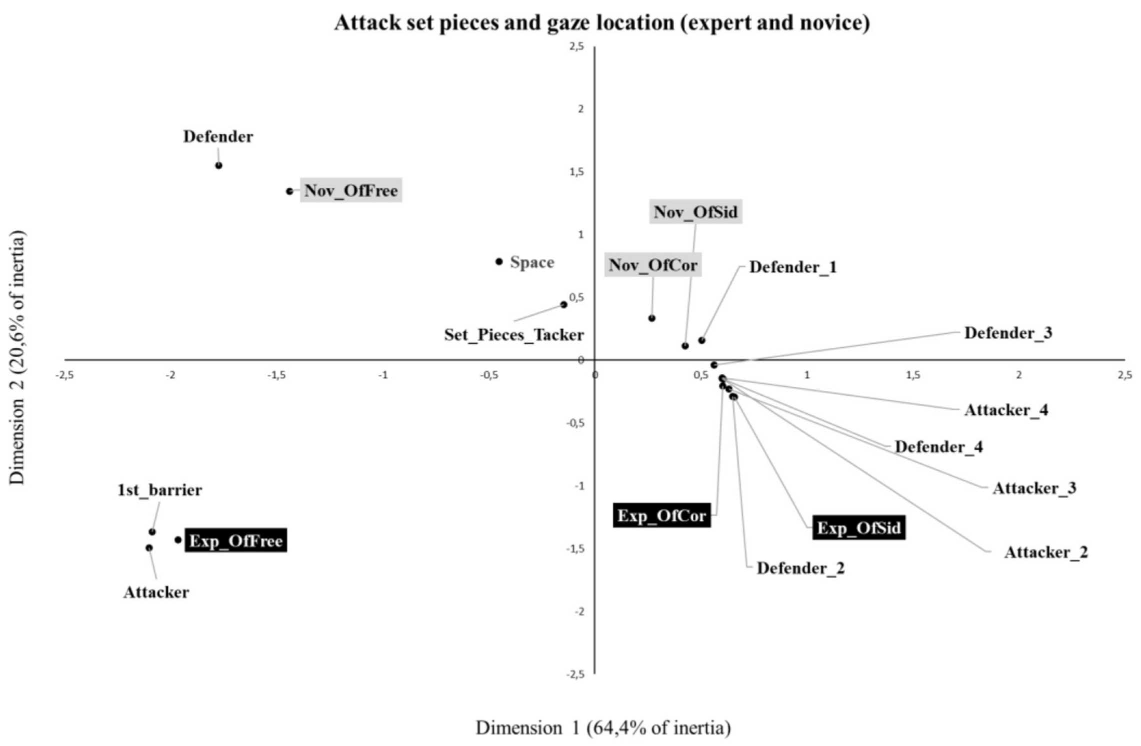


FIGURE 3
Biplot from the correspondence analysis of game moments (attack set pieces) and gaze location.

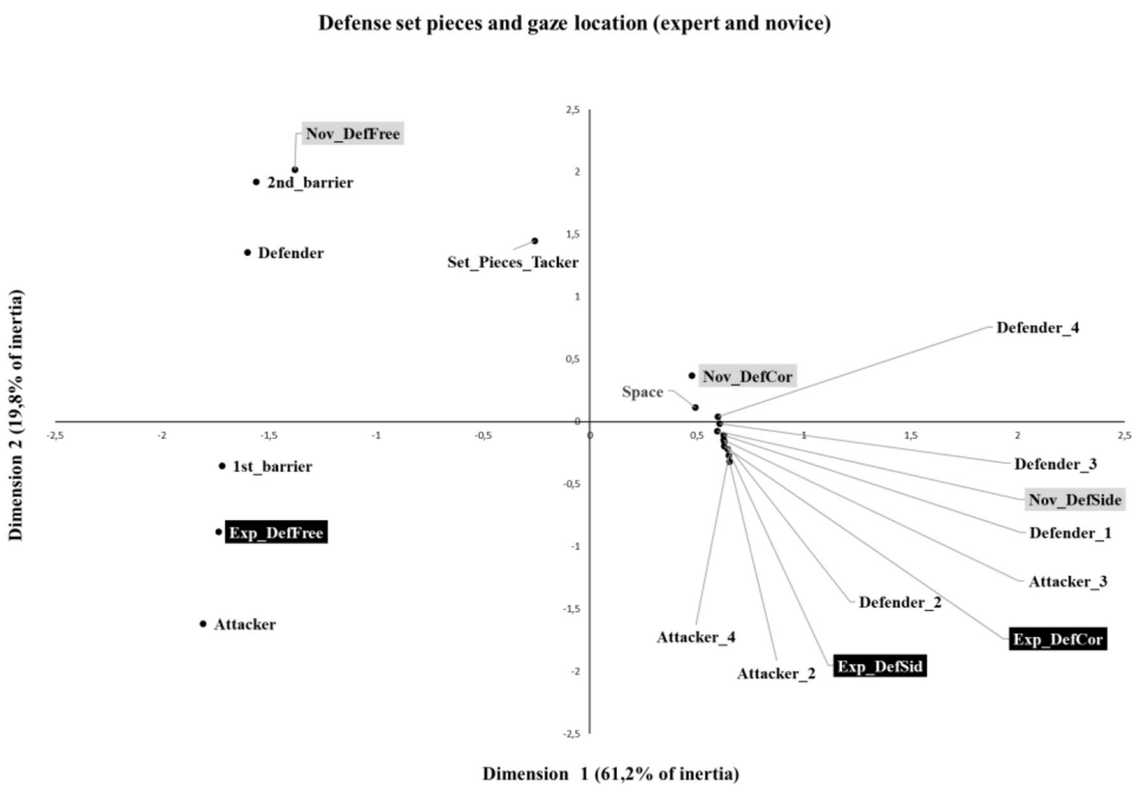


FIGURE 4
Bi-plot from the correspondence analysis of game moments (defense set pieces) and gaze location.

for all the set pieces in the analysis. Expert coaches tend to fix more time on the gaze in attacker 3 (A3), defender 3 (D3), barrier 1st line (B1st), and barrier 2nd line than novices. Moreover, variations in the gaze location between expert and novice coaches were only clear for attack and defense free kicks. The correspondence between attack/defense corner and sideline kicks did not show variations in the correspondence according to the level of expertise.

The current results reinforced the idea that the visual information that sustains understanding of each game moment is specific and needs to be considered in the coaches' development process (Rodrigues et al., 2024). Particularly, in the analysis of free kicks, novice coaches could be aware of the information that they pick up before the ball is in play to anticipate the players' possibilities for action (Araújo et al., 2009). This result highlights the information used to support their decision and contributes to further understanding of the key information that should be considered for each game moment (Mann et al., 2007).

In the context of this study, the set pieces analysis was considered to understand how coaches explore visual information before the ball is in play, i.e., during the time the ball is placed on the ground until it leaves the set piece taker's (SPT) foot in set pieces moments. Therefore, expert coaches revealed longer fixations, often occurring at the end of the set piece. The longer the observation of specific information by the expert coaches in comparison with the novice, even when the ball is stopped, could mean the great ability of coaches to be attuned to the key information of the context (Withagen et al., 2012). In other words, speculatively, the higher values of gaze duration verified by the expert coaches could be the result of a clear knowledge of the spatial-temporal relationships that promote offensive or defensive advantage in game moments of set pieces (Araújo et al., 2009). The observed higher variability in gaze duration values for expert coaches could result from the individual strategies of exploration of opportunities for action according to their own knowledge and game model.

Before the ball is in play, expert coaches tend to fixate more time on attacker 3 (A3), defender 3 (D3), barrier 1st line (B1st), and barrier 2nd line (B2nd) when compared to novices. In set pieces, particularly in the corner and sideline kicks, the attacker and defender 3 are usually the players that directly or indirectly create space to open passing and shooting lines for themselves or other players. Thus, understanding their angular relationship and the space between attacker and defender 3 in relation to the goal is fundamental before the ball is in play to understand the spaces created for shooting (Corrêa et al., 2014; Vilar et al., 2014). In free kicks, expert coaches tend to fixate more time on the barrier 1st line (B1st) and barrier 2nd line (B2nd) compared to novices. This information could be used to understand the number of players in the barrier and their relative position on the field in relation to the ball and goal, and it is crucial in understanding the numerical balance between attackers and defenders in relation to the goal. This understanding is fundamental for prospectively assessing players' possible passing and shooting lines in the field and anticipating possible actions, which is characteristic of expert coaches (Savelsbergh et al., 2002; Mann et al., 2007).

In the analysis of attack and defense set pieces, correspondence analysis shows different visual search strategies and, consequently, gaze locations for each game moment. The variance of dimensions 1 and 2 (i.e., inertia) was almost explained by expert and novice free kicks for both attack and defense, revealing major differences between expert and novice coaches. In contrast, the variance explained by the corner and sideline kicks was too small. This means that there is some correspondence between the gaze locations of expert and novice coaches on corner and sideline kicks, while free kicks present a variation in correspondence between the groups and gaze locations.

The analysis of offensive and defensive free kicks revealed that expert coaches tend to preferentially focus on the informational variables of the barrier's 1st line and attackers without the ball. In contrast, novice coaches, during offensive plays, focus on the variables including defender, space, and set piece taker, while in defensive play, their attention is drawn to the barrier 2nd, defender, space, and set piece taker. In line with previous research, experts appear to be more selective in the informational variables considered to understand the possibilities for action during free kicks compared to novices (Mann et al., 2007). These results suggest that novice coaches may face greater challenges in identifying relevant cues necessary to understand the game's potential actions effectively (Abernethy and Russell, 1987; Abernethy, 1990; Mann et al., 2007; Mitchell et al., 2020).

Regarding offensive and defensive corners and sidelines, novice coaches revealed a close correspondence with the informational variable defender 1. Expert coaches have a close correspondence with the informational variables including attacker 2, attacker 3, attacker 4 and defender 2, defender 3, and defender 4. It is not possible to assume that there is a clear distinction between their visual strategies. Due to the small space in which such moments occur, further research is required to understand whether the lack of differences was related to similarities in the visual search of expert and novice coaches or to methodological issues regarding the identification of the gaze location in the video. Besides the differences in visual strategies between expert and novice coaches identified in this study, questions such as "Are there other relevant sources of information that coaches are looking for?" arise. These questions cannot be answered due to the technological limitations of the device used in this research, but there is a need in the future to capture the real intentions of the expert coaches that guide their gaze, visual search strategies, and their fine perception (Wood et al., 2023). Further research using qualitative methods could be particularly relevant to understanding the intentions and knowledge underpinning expert coaches' behaviors. Furthermore, some research studies need to be conducted in coach education courses to understand the effects of using video analysis as a learning strategy to guide novice coaches' visual search strategies. Despite the results obtained, we acknowledge that the participation of the reduced number of coaches is a limitation of this study. Moreover, for comparison purposes, data collection was carried out using videos and not in the futsal game setting. Further research is required to understand the major differences between coaches' visual search behaviors in analyzing opponent teams during the competition or in the video.

Conclusion

Based on the hypotheses, we can conclude that experts present longer fixations at different locations than novice coaches, particularly for free kicks. To the best of our knowledge, this was the first study to attempt to investigate the visual search strategies of coaches in set pieces, particularly before the ball is in play. These results can improve the understanding of the critical information that may underlie attack and defense set pieces in Futsal. In free kicks, coaches should be particularly concerned about the relationship between attacker and defender 3 and the barrier 1st and 2nd line positions. In corner and sideline kicks, coaches should be particularly aware of the relationship between attackers' and defenders' positions. This information could be used by novice coaches to develop visual search strategies for set pieces before the ball is in play, improving their capacity for anticipation and decision-making during the game.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Ethics Committee of UTAD/CIDESD. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MR: Conceptualization, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. NL: Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. JR: Formal analysis, Investigation, Methodology, Writing – review & editing. JS: Conceptualization, Validation, Writing – review & editing. DA: Conceptualization, Validation, Writing – review & editing. BT: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This study was supported by CIDESD, through national funds of the Portuguese Foundation for Science and Technology, I.P., under the project UID04045/2020.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

References

Abernethy, B. (1990). Expertise in visual search and information pick-up in squash. *Perception* 19, 63–77. doi: 10.1068/p190063

Abernethy, B., and Russell, D. G. (1987). The relationship between expertise and visual search strategy in a racquet sport. *Hum. Mov. Sci.* 6, 283–319. doi: 10.1016/0167-9457(87)90001-7

Aksum, K. M., Magnaguagno, L., Bjørndal, C. T., and Jordet, G. (2020). What do football players look at? An eye-tracking analysis of the visual fixations of players in 11 v 11 elite football match play. *Front. Psychol.* 11:562995. doi: 10.3389/fpsyg.2020.562995

Araújo, D., Davids, K., Cordovil, R., Ribeiro, J., and Fernandes, O. (2009). "How does knowledge constraint sport performance? An ecological perspective," in *Perspectives on Cognition and Action in Sport*, eds. D. Araujo, H. Ripoll, and M. Raab (New York, NY: Nova Science Publishers), 119–132.

Ballet, C., Barreto, J., and Hope, E. and Casanova F. (2023). What is the visual behaviour and attentional effort of football players in different positions during a real 11v11 game? A pilot study. F*1000Res.* 12:679. doi: 10.12688/f1000research.134231.4

Casanova, F., Esteves, P. T., Padilha, M. B., Ribeiro, J., Williams, A. M. and Garganta J (2022). The effects of physiological demands on visual search behaviours during 2 vs. 1 + GK game situations in football: an *in-situ* approach. *Front. Psychol.* 13:885765. doi: 10.3389/fpsyg.2022.885765

Corrêa, U. C., Vilar, L., Davids, K., and Renshaw, I. (2014). Interpersonal angular relations between players constrain decision-making on the passing velocity in futsal. *Adv. Phys. Educ.* 4, 93–101. doi: 10.4236/ape.2014.42013

Hüttermann, S., Noël, B., and Memmert, D. (2018). Eye tracking in high-performance sports: evaluation of its application in expert athletes. *Int. J. Comput. Sci. Sport* 17, 182–203. doi: 10.2478/ijcss-2018-0011

Klostermann, A., and Moeinirad, S. (2020). Fewer fixations of longer duration? Expert gaze behavior revisited. *Ger. J. Exerc. Sport Res.* 50, 146–161. doi: 10.1007/s12662-019-00616-y

Lebeau, J.-C., Liu, S., Sáenz-Moncaleano, C., Sanduvete-Chaves, S., Moscoso, S., Becker, B., et al. (2016). Quiet eye and performance in sport: a meta-analysis. *J. Sport Exerc. Psychol.* 38, 441–457. doi: 10.1123/jsep.2015-0123

Leite, W. S. S. (2012). Analysis of the offensive process of the portuguese futsal team. *Pamukkale J. Sport Sci.* 3, 78–79. Available online at: https://doaj.org/article/e57e0278485a41018cff8615a61d2b49

Mann, D., Williams, A., Ward, P., and Janelle, C. (2007). Perceptual-cognitive expertise in sport: a meta-analysis. *J. Sport Exerc. Psychol.* 29, 457–478. doi: 10.1123/jsep.29.4.457

Mitchell, J., Maratos, F. A., Giles, D., Taylor, N., Butterworth, A., Sheffield, D., et al. (2020). The visual search strategies underpinning effective observational analysis in the coaching of climbing movement. *Front. Psychol.* 11:1025. doi: 10.3389/fpsyg.2020.01025

Roca, A., Ford, P. R., McRobert, A. P., and Mark Williams, A. (2011). Identifying the processes underpinning anticipation and decision-making in a dynamic time-constrained task. *Cogn. Process.* 12, 301–310. doi: 10.1007/s10339-011-0392-1

Rodrigues, M., Leite, N., Ribeiro, J. N., Sampaio, J., Araújo, D., and Travassos, B. (2024). Understanding the futsal game moments through the eyes of futsal coaches: A comparison of expert and novice coaches. *Int. J. Perf. Anal. Sport.* doi: 10.1080/24748668.2024.2354113

Santos, J., Mendez-Domínguez, C., Nunes, C., Gómez, M. A., and Travassos, B. (2020). Examining the key performance indicators of all-star players and winning teams in elite futsal. *Int. J. Perform. Anal. Sport* 20, 78–89. doi: 10.1080/24748668.2019.1705643

Savelsbergh, G. J. P., Williams, A. M., Kamp, J. V. D., and Ward, P. (2002). Visual search, anticipation and expertise in soccer goalkeepers. *J. Sports Sci.* 20, 279–287. doi: 10.1080/026404102317284826

Silva, P., Araujo, D., Davids, K., and Aguiar, P. (2013). Shared knowledge or shared affordances? Insights from an ecological dynamics approach to team coordination in sports. *Sports Med.* 43, 765–772. doi: 10.1007/s40279-013-0070-9

Tonsen, M., Baumann, C. K., and Dierkes, K. (2020). A high-level description and performance evaluation of pupil invisible. *arXiv* [Preprint]. arXiv:2009.00508. doi: 10.48550/arXiv.2009.00508

Travassos, B., Araujo, D., Davids, K., Vilar, L., Esteves, P., Correia, V., et al. (2012). Informational constraints shape emergent functional behaviours during performance of interceptive actions in team sports. *Psychol. Sport Exerc.* 13, 216–223. doi: 10.1016/j.psychsport.2011.11.009

Vickers, J. N. (2016). Origins and current issues in quiet eye research. *Curr. Issues Sport Sci.* 1:11. doi: 10.15203/CISS_2016.118

Vilar, L., Araújo, D., Davids, K., Travassos, B., Duarte, R., Parreira, J., et al. (2014). Interpersonal coordination tendencies supporting the creation/prevention of goal scoring opportunities in futsal. *Eur. J. Sport Sci.* 14, 28–35. doi: 10.1080/17461391.2012.725103

Withagen, R., De Poel, H. J., Araújo, D., and Pepping, G.-J. (2012). Affordances can invite behavior: reconsidering the relationship between affordances and agency. *New Ideas Psychol.* 30, 250–258. doi: 10.1016/j.newideapsych.2011.12.003

Wood, M. A., Mellalieu, S. D., Araújo, D., Woods, C. T., and Davids, K. (2023). Learning to coach: an ecological dynamics perspective. *Int. J. Sports Sci. Coach.* 18, 609–620. doi: 10.1177/17479541221138680

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 09 July 2024
DOI 10.3389/fpsyg.2024.1362976

Check for updates

OPEN ACCESS

EDITED BY
Karen Zentgraf,
Goethe University Frankfurt, Germany

REVIEWED BY
Adam Bruton,
Brunel University London, United Kingdom
Shinji Yamamoto,
Nihon Fukushi University, Japan

*CORRESPONDENCE
Muhammet Cihat Çiftçi
✉ mcciftci@aybu.edu.tr

RECEIVED 29 December 2023
ACCEPTED 10 June 2024
PUBLISHED 09 July 2024

CITATION
Çiftçi MC and Yılmaz B (2024) The effect of action observation and motor imagery on jumping and perceived performance. *Front. Psychol.* 15:1362976.
doi: 10.3389/fpsyg.2024.1362976

The effect of action observation and motor imagery on jumping and perceived performance

Muhammet Cihat Çiftçi* and Baki Yılmaz

Faculty of Sport Science, Department of Sports Management, Ankara Yıldırım Beyazıt University, Ankara, Türkiye

Introduction: Action observation (AO) and motor imagery (MI) are cognitive processes that involve mentally rehearsing and simulating movements without physically performing them. However, the need for the evidence to support influence of imagery on performance is increasing. This study aims to investigate the impact of combining motor imagery with action observation on athletes' performance and performance perception.

Method: Using a pre-test post-test design with a factorial setup, participants were randomly assigned to experimental and control groups. A pre-research power analysis determined the sample size, resulting in 21 voluntary participants (10 male). Opto Jump device recorded drop jump performance measurements, while participants predicted their performance post-motor imagery and action observation practices. The experimental group underwent an 8-week AOMI intervention program, involving 24-minute motor imagery sessions during video observation thrice weekly. Post-test measurements were taken after the intervention.

Results: Results indicated no significant performance increase in the experimental group post-intervention, yet the group showed enhanced performance estimation following the video observation, but not in motor imagery condition. Conversely, this improvement was absent in the control group.

Discussion: Although AOMI intervention didn't enhance physical performance, it has positively affected athletes' perception toward their performance. The findings are discussed in relation to existing literature.

KEYWORDS

action observation, exercise and sports psychology, jumping performance, motor imagery, motor skills

Introduction

Motor simulation theory suggests that individuals can mentally rehearse an action both overtly and covertly through action observation (AO) and motor imagery (MI) in the absence of motor execution (Jeannerod, 1994, 2001). AO and MI describes the simultaneous act of generating, sustaining, and modifying a movement while following a kinesthetic representation of the same action synchronized in time (Vogt et al., 2013). Meers et al. (2020) introduced the visual guidance hypothesis (VGH) as an explanation for how AOMI may impact movement. They propose that during AOMI, motor imagery

10.3389/fpsyg.2024.1362976

takes precedence, with the action observation component serving merely as an external visual guide that enhances the vividness of MI generation. This suggests that AO does not activate a separate motor representation during AOMI, but rather reinforces the motor representation stemming from MI. VGH posit that AOMI has the potential to influence motor skill execution beyond isolated AO or MI by enhancing activity in motor regions of the brain.

Studies evaluating the impact of the AOMI approach on various domains (neurological, behavioral, psychological) exist in the literature. When examined at from a cognitive perspective, motor learning is influenced by changes in mental representations of motor skills (Schack, 2004). These mental representations consist of cognitive information related to executing the movement, including required body postures, relevant movement components, and associated sensory outcomes (Wright et al., 2022). For instance, when a skill is about to be performed by an athlete, the movement is guided by evoking mental representations of the skill. Considering that AO and MI develop mental representations through different mechanisms, combining these two processes in an AOMI intervention is suggested to be more effective than independent AO or MI in enhancing the mental representations of the action in long-term memory (Kim et al., 2017; Wright et al., 2022). From neurological perspective, motor simulation theory explains how activations in the neural network system may cause changes. In the past decade, research on AOMI interventions has consistently shown increased activity in motor regions of the brain compared to independent AO or MI. The evidence suggests an activation in overlapping brain regions during the imagery, observation, or execution of movements (Hétu et al., 2013; Hardwick et al., 2018; Wright et al., 2018). However, the direct link between increased neurophysiological activity during AOMI and improved performance is yet to be established (Frank et al., 2020). However, the similarity in neural activation during imagery does not fully explain skill development in sports performance and sport-specific contexts. The processes of planning, programming, monitoring, and controlling movements during motor imagery suggest that the underlying mechanism of this method is much more diverse and intricate (see e.g., O'Shea and Moran, 2017). The discussion toward motor simulation theory raised by O'Shea and Moran (2017) highlights the importance carefully examining the causes of behavioral consequences of imagery interventions.

In terms of behavioral outcomes, Smith and Holmes (2004) demonstrated that participants receiving AOMI intervention showed higher performance in golf putting tasks compared to those engaged solely in motor imagery. Similarly, in a study by Wright and Smith (2009), participants receiving an intervention similar to AOMI exhibited increased forearm strength compared to those engaged only in motor imagery. The effectiveness of AOMI in enhancing performance stems from eliminating the necessity to create mental movement imagery through visual input (Holmes and Calmels, 2008). Hence, participants do not exert additional effort to generate mental images of the desired movement, allowing them to focus on the kinesthetic aspects of the desired skill by clearing attentional resources. Moreover, visual, auditory, or temporal cues related to motor skills can be conveyed to participants through video (Eaves et al., 2016b). Studies examining the acute effects of imagery interventions on performance generally provide evidence related to cognitive components in tasks such as balance, movement precision (Smith and Holmes, 2004; Romano-Smith et al., 2018; Wright et al., 2018), or predominantly maximal isometric muscle contractions (Wright and Smith, 2009; Di Rienzo et al., 2015, 2019). A detailed evidence can be found in the meta-analysis conducted by Chye et al., 2022 where authors suggest that AOMI influences sport-specific movement outcomes moderate to high-level. It can be drawn from the existing literature that the effectiveness of imagery interventions on jumping requires attention.

Jumping, a complex human movement that necessitates intricate motor coordination between upper and lower body segments, involves the assessment of the propulsive force of the lower extremities during vertical jumps to assess the explosiveness of both sedentary individuals and elite athletes (Markovic et al., 2004). In this study, jumping performance was chosen as a fundamental measurement tool due to its widespread use in evaluating sports performance and commonly being a parameter used to evaluate athletes' physical abilities. Especially considering the importance of jumping ability in terms of many sports performances (Young et al., 1995; Gorostiaga et al., 2004; Walsh et al., 2004; Mikkola et al., 2007), examining motor imagery in this context is necessary as well. However, to the best of our knowledge, the number of studies examining the effect of imagery on jumping performance is quite limited in the sports psychology literature. The closest studies have usually examined the effect of motor imagery on jumping performance.

A recently conducted meta-analysis by Lindsay et al. (2023) included only one study (Olsson et al., 2008) examining the impact of imagery on jumping performance. In this study by Olsson et al. (2008), high jumpers showed no significant difference in jump heights following imagery sessions, yet the group practicing imagery in addition to training showed a notable improvement in technical skill, particularly in bar clearances. Another study by Battaglia et al. (2014) with gymnasts revealed a positive impact of motor imagery on jumping performance parameters. On the contrary, Avila et al. (2015) found no significant difference in active jumping performance between groups practicing imagery compared to those who did not. Additionally, Bergmann et al. (2013) examined the effect of motor imagery on depth jumps, indicating a rather limited effect. They propose that in addition to, participants' predisposition toward the motor skill used during the experimental task might have influenced this outcome.

The utilization of the jumping paradigm in this research aligns with the strength approach to assess the effectiveness of AOMI intervention. This choice is deliberate because prior imagery research predominantly employed tasks with a substantial cognitive aspect, such as balance, precise movements, or maximal isometric muscle contractions (Bergmann et al., 2013; Hardwick et al., 2018; Di Rienzo et al., 2019; Simonsmeier et al., 2021). AOMI could be an important tool for enhancing jumping performance because the nature of the jumping movement requires the interaction of both visual and kinesthetic elements (Wright et al., 2022). AOMI can support the formation of mental representations of the jumping movement by observing the correct form and technique of the jump (Eaves et al., 2016a; Kim et al., 2017; Bach et al., 2022). This method can enhance movement performance by increasing brain activation of the muscle groups actively used during jumping. AOMI can help automate motor skills and enhance performance by mentally rehearsing the movement (Nedelko et al., 2012; Lee et al., 2021). AOMI can provide athletes with visual feedback to understand and optimize the complexity of the jumping movement (Kraeutner et al., 2020).

Although many studies suggest the impact of AOMI interventions on performance (Eaves et al., 2016b; Simonsmeier et al., 2021; Chye et al., 2022), varying outcomes regarding its influence specifically on jumping performance indicate a lack of consensus (Olsson et al., 2008; Bergmann et al., 2013; Battaglia et al., 2014; Avila et al., 2015). Despite the strong evidence supporting the AOMI effectiveness in certain movement classifications the lack of consensus in jumping performance literature requires more attention. Based on this, we developed a paradigm to assess the perception of the participants toward the intervention. This discriminate our experiment in terms of finding the perceived benefit of the AOMI interventions from individual perspective. By doing so, we hypothesized that individuals in intervention group would perceive the imagery more beneficial compared to their counterparts. It is also essential to note that measuring a motor skill which is widely accepted as an indicator of athletic performance is a necessity of imagery studies to highlight its' effectiveness. Therefore, we tend to believe that conducting research involving imagery intervention utilizing the Action Observation with Motor Imagery (AOMI) method may influence performance. Therefore, the need arose to conduct an eight-week intervention study incorporating AOMI intervention to investigate its potential impact on performance.

Materials and methods

Research design

A randomized controlled 2 × 2 factorial design was used in this experimental study (Goodwin and Goodwin, 2016; Passer, 2020). The independent variables in this study were (1) type of intervention (AOMI vs. control) and (2) time (pre-test vs. post-test). The dependent variables were (1) drop jump performance, as measured by the Opto Jump device, and (2) perceived performance estimation, as predicted by the participants after the intervention. This design allowed us to investigate both the main effects of each independent variable and the interaction effects between them on the dependent variables. By employing this factorial design, we were able to systematically explore the influence of the combined AOMI intervention on both objective performance metrics and subjective performance perceptions.

Participants

Students from the faculty of sport sciences were recruited for the study. Inclusion criteria stipulated participants to be actively involved in sports, right-handed, free from neurological conditions, and possessing normal visual acuity. *A priori* power analysis determined that a group size of 20 participants was adequate (Effect size $f = 0.35$, $\alpha = 0.05$, Power = 0.80). 30 participants (15 males) were hired for study to account for possible dropouts. Eight participants dropped out of the study and one outlier from the experimental group was excluded based on statistical methods leaving 21 participants (10 males, 11 females) for final analysis. The experimental group had an average age of 20.20 years (SD = 1.81), height of 171.30 cm (SD = 6.44), and weight of 62.70 kg (SD = 13.89). The control group had an average age of 19.09 years (SD = 0.53), height of 178.18 cm (SD = 7.76), and weight of 72.27 kg (SD = 6.88). Imagery ability, assessed using the MIQ-R, showed pre-test kinesthetic scores of 5.95 (SD = 0.80) and post-test scores of 6.00 (SD = 0.62) for the experimental group, compared to 5.43 (SD = 1.01) and 5.55 (SD = 0.52) for the control group. Pre-test visual scores were 6.42 (SD = 0.44) and post-test scores were 6.20 (SD = 1.40) for the experimental group, while the control group had pre-test scores of 6.30 (SD = 0.56) and post-test scores of 6.30 (SD = 0.70).

Measurements

Movement imagery questionnaire-revised form

Participants' motor imagery abilities were assessed using the Movement Imagery Questionnaire-Revised Form (MIQ-R), adapted into Turkish by Akkarpat (2014) from Monsma et al. (2009)'s original questionnaire. This tool evaluates visual and kinesthetic imagery across four movements: jumping, arm movement, toe touching, and knee raising. Participants completed three stages for each movement: assuming the initial position, physically performing the movement, and mentally recreating the movement without executing it physically. They rated the ease of visualizing/feeling each movement on a scale from 1 to 7. To ensure understanding, participants were given a demonstration and allowed to physically perform the movements before the assessment.

Likert measurements

Participants were requested to provide self-assessments of their motivation levels throughout the course of the experimental procedures. To facilitate this evaluation, participants were instructed to employ a 10-point Likert scale, with ratings ranging from 1 ("indicating a low level of motivation") to 10 ("indicating a high level of motivation"). Additionally, participants were asked to evaluate the mental difficulty they perceived during each of the imagery sessions. This assessment was conducted using a single statement: "What is the perceived level of mental difficulty experienced during the imagery activity you engaged in?" Responses were recorded on a 10-point Likert scale, spanning from 1 ("indicating not at all difficult") to 10 ("indicating a very high level of difficulty"). It's noteworthy that this methodology, involving a single question to assess motivation in relation to experimental processes and perceived difficulty during imagery sessions, has been previously utilized in an imagery study conducted by Di Rienzo et al. (2019).

Performance measurement

Participants underwent three weeks of practice trials for Drop Jump (DJ) before the pre-test measurements. Both groups familiarized themselves with these jumps and performed them in consistent environmental conditions. Before the jumps, participants completed warm-up exercises, including stretches, body-weight squats, and a short run. The DJ measurements followed a full rest period after the warm-up, using the OptoJump

Next® device. This device has high reliability (ICC 0.88–0.98), validated in sports sciences (Glatthorn et al., 2011; İnce, 2019) and was used with manufacturer-advised protocols for DJ measurements. During assessments, participants executed a vertical jump at maximum speed, adhering to specific body positions. Any deviation led to exclusion or repeat of measurements, with the average of two successful trials determining performance (Battaglia et al., 2014).

Perceived performance measurement

Following the completion of physical performance measurements, perceived performance predictions were measured. During both the pre-test and post-test stages, each participant was instructed to indicate their perceived performance with implementing single bout of action observation and motor imagery practice. While observing the video participants were tried to imagine drop jump and indicate how high they might have jumped in Action Observation Perceived Performance (AOPP) condition. During the AOPP session, participants were asked to conduct simultaneous action observation and motor imagery. As for the Motor Imagery Perceived Performance (MIPP) condition, they executed a single bout of imagery of without visual aid. In the MIPP condition, participants were first instructed to mentally rehearse the jumping task and then indicate their perceived jump scores. Each participant completed single bout of AOP and MIP trial in random order during both the pre-test and post-test measurement sessions to prevent sequential effects. Perceived performance measurement wasn't repeated throughout the intervention phase. This method ensured consistent measurement of perceived performance in both stages of the study.

Action observation and motor imagery intervention

After the pre-test measurements, the experimental group commenced the intervention program with meticulously produced videos displaying DJ movement, featuring selected models from the Faculty of Sports Sciences to match participants' physical abilities. Male models were used for male participants and female models for females, enhancing behavioral congruence. These movements were recorded at 60 frames per second using a GoPro Hero 5 Black action camera. In alignment with established literature recommendations, the videos were recorded from a first-person perspective due to its known efficacy in more profoundly engaging the motor system (Alaerts et al., 2009). This perspective not only provides a closer behavioral match but also significantly enhances overall efficacy (Wakefield et al., 2013).

Before the intervention, participants received comprehensive training in imagery techniques, including the PETTLEP model, emphasizing sensory effects like environmental stimuli, muscle activation, heart rate, and postural changes (Lang et al., 1992; Romano-Smith et al., 2018). Prioritizing sensory effects significantly improves imagery and animation skills (Williams et al., 2013) and animation skills (Wakefield and Smith, 2009).

The intervention ran three times weekly for 8 weeks, following prior research recommendations (Toth et al., 2020; Lee et al., 2021). Each 24-min imagery session comprised 4-min segments with 1-min breaks (4 min. 6 blocks totalling 30 min. including the breaks), based on guidance from Lee et al. (2021). Sessions were held in the same laboratory as the initial measurements. The practitioner overseeing the sessions was blind to specific research objectives, aiding participants through each 4-min block and emphasizing the importance of the 1-min breaks.

Manipulation check

Imagery diaries served as a manipulation control in the study. Participants were provided with diaries and instructed to complete them to verify adherence to the imagery session instructions throughout the study's duration. Furthermore, it is worth noting that maintaining diaries to document specific emotional experiences during each imagery session, any encountered difficulties, or feedback on the intervention method, aligns with practices in prior imagery research (Smith et al., 2020).

Procedure

The participants, upon giving their consent, were enrolled in the study and assigned to either the experimental or control group using the last four digits of their student numbers. They were informed about the withdrawal option and confidentiality measures. Participants attended the laboratory for eight weeks to follow the intervention program. The study's nature was kept confidential until data collection was complete, focusing on investigating imagery's impact on psychological variables. Initial assessments involved imagery ability measurement with the Movement Imagery Questionnaire-Revised Form. Participants were familiarized with performance measurements using the Opto Jump device for three weeks. DJ exercises were practiced 3 times for each week during familiarization. Pre-test measurements were taken after a 7-day rest period to avoid muscle strain. Practice sessions aimed to mitigate bias from physical predispositions, learning effects, and performance variations. Following familiarization, pre-test measurements were implemented along with the perceived performance prediction estimations. They were welcomed by the first author when they arrived the laboratory and informed about the test procedures. Participants underwent 10 min warm-up sessions before engaging in drop jumps. They were considered to be ready to perform the tests after having a short rest (3–5 min.) from warm-up. The AOMI intervention was initiated following the completion of pre-test measurements. Participants were instructed to practice action observation and motor imagery during intervention sessions with fully focus on the movement. Sessions were supervised in a distraction-free laboratory setting. The PETTLEP principles were introduced and ensured to be implemented, assisting participants in adapting these principles to their imagery skills.

In the pre and post-test participants tried to predict their jump heights after a single bout of AOP and MIP in random order. In the AOP performance estimation attempt, they observed a video of model athlete performing the task. First author, who also conducted the tests, provided feedback on jump height and ground contact time durations but this feedback was not provided in the MIP attempts. During the intervention imagery sessions lasted 24 min, divided into 4-min blocks with 1-min breaks in Kraeutner et al. (2020). At each session's end, a verbal imagery scenario was presented as a warm-up exercise, followed by watching jump videos, simulating drop jumps in sync with the displayed video. Completion of a 30-min session equated to one Action Observation and Motor Imagery (AOMI) intervention session. At the end of the study, participants were thanked and debriefed about the experimental procedure (Supplementary Table 1).

Statistical analysis

SPSS version 22 was used for data analysis, presenting descriptive statistics (means and standard deviations). Normality was confirmed in dependent variables for both groups using the Shapiro–Wilk test, histograms, and probability plots. We identified the extreme outlier statistically by assessing histograms, probability plots, and conducting the Shapiro–Wilk test for normality, confirming its status based on 1.5 times the interquartile range (IQR) thresholds, and subsequently excluded it from the dataset. For detecting possible differences between groups, independent samples t-tests were employed at pre-test. The two-way mixed ANOVA (2×2) was implemented to find intervention effect and between-group differences.

We utilized the Intraclass Correlation Coefficients (ICC) to assess test-retest reliability, following Koo and Li's (2016) classification system. Based on their work, ICC values were categorized as follows: ≤ 0.49 poor, ≥ 0.50 ICC < 0.75 moderate, ≥ 0.75 ICC < 0.9 (good), and ≥ 0.9 excellent (Koo and Li, 2016). Cohen's d effect sizes were used to determine the impact of the independent variable on dependent variables between pre-test and post-test measurements. These effect sizes were accompanied by their 95% confidence intervals. Cohen's classifications—small (0.2), medium (0.5), and large (0.8)—were adopted to interpret the effect sizes (Cohen, 2013). A significance level of $p < 0.05$ was used for all statistical tests.

Results

Normality tests

The Shapiro–Wilk test confirmed normal distribution for most pre-test and post-test data, validating the use of parametric tests. Deviation in one parameter's pre-test values resulted from a single outlier but didn't significantly affect overall normality. Hence, outlier removal was deemed unnecessary. Participant demographics indicated diverse sports backgrounds in both groups. Exercise frequency for the experimental group was 3.70 ± 1.70 times/week (62.50 ± 15.85 mins/session) and for the control group, 4.45 ± 0.68 times/week (68.63 ± 13.24 mins/session). No significant difference in motivation levels between groups was observed ($t = 0.689$, $p = 0.499$). Participants displayed consistent kinesthetic and visual imagery abilities across pre-test and post-test phases (kinesthetic: $t = 1.28$, $p = 0.215$, $t = 1.817$, $p = 0.085$; visual: $t = 0.579$, $p = 0.569$), indicating stable imagery skills. Additional demographic details are provided in Table 1.

Intra-class correlation coefficient

The intraclass correlation coefficient (ICC) was computed to assess the reliability of the measurements. The ICC value obtained for jump performance was calculated as reliable scores (ICC ≥ 0.88) except for the DJ GCT. This high ICC values signifies that the measurements are consistent and reliable in actual performance recordings. Conversely, ICC obtained for performance predictions showed poor reliability (ICC ≤ 0.49) (Table 2).

Performance results

The repeated measures multivariate analysis of variance (ANOVA) conducted to assess the impact of the AOMI intervention program on performance revealed a significant main effect of time on drop jump performance in within-group comparisons [$F(1, 19) = 14.491$, $p = 0.001$, ηp2 = 0.433]. Conversely, there was no significant main effect found between groups [$F(1, 19) = 0.885$, $p = 0.359$, ηp2 = 0.045]. However, significant main effect was found in the group-time interaction [$F(1, 19) = 4.435$, $p = 0.049$, ηp2 = 0.189]. Pairwise comparisons were conducted to assess differences between experimental and control groups at two time points for the main interaction effect (Supplementary Figure 1). The results indicate no significant differences between groups at either time point (Pre-test: MD = −3.017, SE = 2.414, $p = 0.227$, 95% CI [−8.069, 2.035]; Post-test: MD = −1.184, SE = 2.126, $p = 0.584$, 95% CI [−5.634, 3.266]). All comparisons were adjusted using Bonferroni correction for multiple comparisons.

Supplementary Figure 2 demonstrates that there was no significant main effect of time in the within-group comparisons for the DJ AO perceived performance prediction [$F(1, 19) = 0.085$, $p = 0.774$, ηp2 = 0.004]. Similarly, no significant main effect was found between the groups [$F(1, 19) = 0.141$, $p = 0.711$, ηp2 = 0.007]. However, upon examining the group-time interaction, a significant interaction effect was found [$F(1, 19) = 5.795$, $p = 0.026$, ηp2 = 0.234]. The mean of the experimental group was significantly increased from pre-test (M = 28.1, sd = 2.33) to post-test (M = 30.95, sd = 7.37) compared to control group. There was no significant main effect of time within-group comparisons for the DJ MI perceived performance prediction [$F(1, 19) = 2.791$, $p = 0.111$, ηp2 = 0.128] and no significant main effect between groups was found [$F(1, 19) = 0.705$, $p = 0.411$, ηp2 = 0.036] (Supplementary Figure 3). Group-time interaction was also not significant in the same variable [$F(1, 19) = 0.003$, $p = 0.955$, η p2 = 0.001].

Discussion

This study investigates the impact of motor imagery during movement observation on jump performance over a 12-week period. The main outcome of the study points out that experimental group receiving AOMI intervention experienced lower decline in jump performance from pre to post-test compared to the control group but the difference was not significant. This finding indicates that, contrary to our hypothesis, the AOMI intervention did not enhance drop jump performance as expected. Given these results, further investigation is needed to understand the

TABLE 1 Comparison of participants' demographic variables.

Group	Experimental		Control		Independent sample *t*-test	
Variables	Mean	Sd.	Mean	Sd.	*t*	*p*
Age (years)	20.20	1.81	19.09	0.53	1.861	0.091
Height (cm)	171.30	6.44	178.18	7.76	−1.722	0.101
Weight (kg)	62.70	13.89	72.27	6.88	−1.970	0.071
Number of exercises per week	4.10	1.10	4.45	0.68	−1.308	0.216
Training duration per session	62.50	15.85	68.63	13.24	−0.966	0.346
Pre-test MIQ-R (kinesthetic)	5.95	0.80	5.4318	1.01	1.283	0.215
Post-Test MIQ-R (kinesthetic)	6.00	0.62	5.5455	0.52	1.817	0.085
Pretest MIQ-R (visual)	6.42	0.44	6.2955	0.56	0.579	0.569
Post-Test MIQ-R (visual)	6.20	1.40	6.2955	0.70	−0.199	0.844
Motivation to research participation	8.90	1.10	8.455	1.75	0.689	0.499

TABLE 2 Demonstration of intra-class correlation coefficients.

Variable		ICC	95% confidence interval		F test with true value 0			
			Lower bound	Upper bound	Value	df1	df2	*p*
DJ MI PPP	Single measures	0.197	−0.201	0.558	1.537	20	20	0.172
DJ AO PPP	Single measures	0.496	0.084	0.761	2.888	20	20	0.011
DJ ELV	Single measures	0.880	0.762	0.946	40.487	20	60	0.000
DJ FT	Single measures	0.890	0.777	0.951	44.791	20	60	0.000
DJ GCT	Single measures	0.681	0.496	0.834	9.548	20	60	0.000

underlying mechanisms and potential factors influencing the effectiveness of AOMI interventions on athletic performance. The findings of our study seems to be contradictory to several previous studies (Yue and Cole, 1992; Ranganathan et al., 2004; Collet et al., 2011; Di Rienzo et al., 2015, 2019; Iacono et al., 2021). A study by Smith et al. (2020) suggested an increase in biceps strength following imagery intervention. Although various studies support the opposite, a meta-analysis conducted by Paulo Manochio et al. (2015) suggests that the evidence does not support the idea of imagery being an effective tool to enhance strength gains. Inconsistent results in the literature raise the question of whether imagery interventions, whether they include video observations or not, indirectly facilitated improvements in participants' motor skills. However, due to the absence of video analysis methods, technical alterations related to jump performance could not be determined. For instance, Olsson et al. (2008) observed advancements in athletes' technique despite no increase in jump heights in their study. Although our study's results align with the absence of an increase in jump heights, the inability of our study to detect sport-specific technical improvements differs. This suggests that while the AOMI intervention may not affect performance directly, it may contribute to learning outcomes in jumping technique. Nonetheless, we did not measure biomechanics in our study to support this notion. In general, the data imply that the sole implementation of AOMI for imagery did not necessarily facilitate performance increase. These findings, consistent with certain studies (Smith et al., 2020), suggest limited performance changes when comparing imagery-only to physical application (Kraeutner et al., 2020).

Moreover, differences in the imagery protocols used, particularly in the content of instructions and mechanical characteristics of exercises, could influence the contradictory outcomes. Although the AOMI protocol outlined detailed movement steps, the absence of prior experience might have affected the performance. Concrete embodiment theories emphasizing the influence of prior experiences on learning processes (Mulder et al., 2004; Olsson and Nyberg, 2010; O'Shea and Moran, 2017; Iacono et al., 2021) and studies demonstrating how imagery builds upon previous physical experiences by modulating brain activation (Kraeutner et al., 2018). In another study by Collet et al. (2011), MI intervention was found to increase the number of maximum repetitions in leg press; however, no significant difference was observed in bench press between groups. Individual factors such as participants' experience levels in resistance exercises and muscular adaptations might explain this discrepancy. These arguments contribute to our understanding of how previous physical experiences influence imagery and learning processes.

The question of how specific prior experience needs to be to influence imagery arises regarding its effectiveness. Olsson et al. (2008) compared high jump athletes with a control group of novices in an attempt to answer whether effectively imagining a skill previously experienced is feasible. Their study provided evidence that for the mental imagery of a complex skill, individuals need well-established motor representations, which subsequently transform into brain activities shaping motor representations. The findings suggested that imagery training reduced activity in the parietal cortex, resulting in more automatic imagery and a more easily accessible, efficient motor representation during motor performance. Considering the similar effects of observing and imagining movements, the role of physical experience during observation should also be considered. In a study by Aglioti et al. (2008), elite basketball players were compared with expert spectators (former basketball players who had stopped playing) and novices in predicting movement outcomes. The findings indicated that only elite basketball players were successful in predicting outcomes, suggesting that motor representations shaped by specific physical experiences are highly specific. Therefore, merely having prior high-level expertise in a particular task might not suffice for predicting the outcomes of movements; rather, the physical experience needs to be relatively recent. Balser et al. (2014) examined the impact of expertise on brain activation in expert volleyball and tennis players while predicting serve shots in both sports. Results showed that while athletes predicted serves faster in their own sport, neural activation in the observation network was higher in the unfamiliar sport. Additionally, Del Percio et al. (2008) highlighted that experienced athletes exhibited more effective neural cortical activity compared to novices, indicating higher neural focus. Hence, considering the relatively limited prior experience in active and depth jumps among our study participants and the time gap due to the pandemic before the research process, it is presumed that the lack of recent experience might have influenced our study's outcomes.

In the study, participants were also asked to indicate their perception toward performance during imagery. They were tasked to estimate their performances after two different conditions: engaging in imagery and watching videos. Findings revealed that while participants predicted decreased jump scores, their estimated performance perceptions were higher in AO condition. This outcome is noteworthy, although the results was statistically insignificant. Participants reported a decline in imagery condition over time but noted an improvement in their performance after observing the role model. This indicates that relying solely on imagery might not foster performance necessarily, possibly due to participants struggling initially to clearly follow imagery instructions and control mental images (Holmes and Calmels, 2008). Additionally, there is a recognized limitation in researchers' ability to monitor participants' motor images (Wright et al., 2022). However, action observation might facilitate participants in better understanding and controlling their imagery performance (Olsson and Nyberg, 2010). Observation through video feedback enhanced participants' performance. This suggests that conveying visual information allows participants to associate their kinesthetic sensations with the execution of the movement (Eaves et al., 2016a,b). As video observation is considered a passive process accessing the motor system through the observation of motor actions instead of imagery, this notion aligns with the mirror neuron system (Rizzolatti and Craighero, 2010).

The findings indicate the positive impact of video watching on the effectiveness of imagery in performance. However, uncertainties persist regarding whether subjective awareness serves as a precise mechanism to determine the completion of a movement simulation (O'Shea and Moran, 2017). The performance enhancement observed in video watching following the AOMI intervention provides significant hints on how visual inputs facilitate the improvement of participants' mental representations and subsequently enhance their performance. Participants' inclination to improve their performance by utilizing cognitive mental representations rather than directly controlling their movements warrants attention. Research emphasizes the activation of different mechanisms through visual and mental exercises (Kim et al., 2017). For instance, it is proposed that visual inputs could develop mental representations to sequence and time the components of movement execution (Frank et al., 2020). In this context, it is considered that visual inputs offer an advantage to the experimental group in creating relevant motor representations.

Additionally, individuals are reported to observe their own practices to enhance their performance and refine their visual perceptions (Hars and Calmels, 2007). Particularly, the perception of observing others as a means to enhance performance suggests an effective strategy for developing participants' cognitive abilities. Participants who received AOMI intervention stated an improvement in their performance post-observation rather than during mental imagery, possibly indicating a more effective engagement of cognitive functions during simulation (O'Shea and Moran, 2017). Research suggests that observing movement activates different neural connections compared to motor imagery (Hardwick et al., 2018). According to the motor simulation theory, individuals can mentally construct images related to any motor skill, implying that visual inputs support learning (Jeannerod, 2001). This aligns with MST's proposition that the restriction of implicit skills (execution of movement) during imagery is a part of the simulation process (Jeannerod, 2004, 2006).

Participants receiving AOMI intervention might have aimed to avoid engaging in the actual execution of movements during imagery rather than seeking performance enhancement. The constriction of movement during MI might reduce the possibility of carrying out the action by imposing limitations on cognitive processing. These constrictive processes are suggested to play a role in guiding motor orientation and inhibiting the execution of motor programs (Richard Ridderinkhof et al., 2011). Bach et al. (2014) discovered that participants found it more challenging to respond to stimuli with the limbs engaged in MI, leading them to respond with other body parts. This supports the close relationship between intentional processes in motor planning and constraining processes, potentially clarifying the results of the study. Furthermore, participants who received AOMI intervention expressing an increase in their performance post-observation might indicate the impact of video observation on their self-efficacy beliefs (Ste-Marie et al., 2012). Observation-based learning is highlighted to influence movement dynamics more than the output of movement, suggesting that those in the AOMI group might have perceived an improvement in their performance based on the role model in the video (Ashford et al., 2006).

Limitations and implications

There are several implications and limitations that should be considered when reading this article. The lack of performance improvement and, in some cases, a decline observed in participants undergoing the 8-week AOMI intervention calls for careful consideration of these results. Anticipating that imagery alone would impact performance might lead to undesirable outcomes. The research also highlighted that AOMI intervention not only influenced performance but also affected perceptions toward performance. While experimental group (EG) participants predicted increased performance after video observation, the control group's predictions were opposite. This indicates that

AOMI over time positively influenced participants' perceived benefit from the intervention. These outcomes suggest that in sports psychology practices, imagery interventions can be utilized as a tool to influence athletes' self-efficacy perceptions.

Nonetheless, the study faced limitations that need to be considered in result interpretation. Demographic variations among participants could yield different results, particularly when applied to elite athletes or patient groups. Additionally, the absence of any physical training alongside the AOMI intervention restricts the evaluation to purely imagery-based effects. This study encountered constraints due to restricted access to long-term training routines for participants as there was last remaining effects of pandemic habits. This circumstance should be considered when interpreting results. Furthermore, the low intra-class correlation values imply the need for cautious evaluation of self-report performance predictions. The research highlighted that not all motor imagery programs utilized in practice exert the same level of influence on enhancing performance parameters. However, the specific reasons behind the varying efficacy levels among these programs weren't extensively explored. Further investigation into the specific elements contributing to program effectiveness could provide a deeper understanding. The findings of the study emphasize the necessity to evaluate AOMI interventions across a broad spectrum of athletes to understand the effectives of it in difference disciplines.

The findings of this study indicate that motor imagery programs may not necessarily show a significant effectiveness in improving performance outcomes. It has been revealed that not every motor imagery program used in practice is equally effective in enhancing performance parameters. Therefore, decisions to choose motor imagery interventions for developing the performance should be based on after careful planning. Additionally, the study suggests that implementing motor imagery along with video observation may have positive effects on shifting participants' perceptions of their performances. However, it is emphasized that when developing imagery intervention programs, applied psychologists must pay attention to participants' prior experiences of relevant motor skills. The findings above shows important factors to consider when evaluating the effects of motor imagery programs on performance.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Social and Humanities Ethics Committee—Ankara Yıldırım Beyazıt University (Folder no: 2021-142, date: 15.03.2021-72). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MÇ: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. BY: Conceptualization, Investigation, Visualization, Writing – review & editing.

Funding

The authors declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2024.1362976/full#supplementary-material

References

Aglioti, S. M., Cesari, P., Romani, M., and Urgesi, C. (2008). Action anticipation and motor resonance in elite basketball players. *Nat. Neurosci.* 11, 1109–1116. doi: 10.1038/nn.2182

Akkarpat, I. (2014). *Farklı Yaş Gruplarında Basketbolda Imgelemenin Serbest Atış Performansı, Özgüven ve Kaygı Üzerine Etkisi*. Master Thesis. Ankara: Hacettepe University.

Alaerts, K., Heremans, E., Swinnen, S. P., and Wenderoth, N. (2009). How are observed actions mapped to the observer's motor system? influence of posture and perspective. *Neuropsychologia* 47, 415–422. doi: 10.1016/j.neuropsychologia.2008.09.012

Ashford, D., Bennett, S. J., and Davids, K. (2006). Observational modeling effects for movement dynamics and movement outcome measures across differing task constraints: a meta-analysis. *J. Motor Behav.* 38, 185–205. doi: 10.3200/JMBR.38.3.185-205

Avila, B. J., Brown, L. E., Coburn, J. W., and Statler, T. A. (2015). Effects of imagery on force production and jump performance. *J. Exerc. Physiol. Online* 18:42.

Bach, P., Allami, B. K., Tucker, M., and Ellis, R. (2014). Planning-related motor processes underlie mental practice and imitation learning. *J. Exp. Psychol.* 143:1277. doi: 10.1037/a0035604

Bach, P., Frank, C., and Kunde, W. (2022). Why motor imagery is not really motoric: towards a re-conceptualization in terms of effect-based action control. *Psychol. Res.* doi: 10.1007/s00426-022-01773-w Online ahead of print.

Balser, N., Lorey, B., Pilgramm, S., Naumann, T., Kindermann, S., Stark, R., et al. (2014). The influence of expertise on brain activation of the action observation network during anticipation of tennis and volleyball serves. *Front. Hum. Neurosci.* 8:568. doi: 10.3389/fnhum.2014.00568

Battaglia, C., D'Artibale, E., Fiorilli, G., Piazza, M., Tsopani, D., Giombini, A., et al. (2014). Use of video observation and motor imagery on jumping performance in national rhythmic gymnastics athletes. *Hum. Movement Sci.* 38, 225–234. doi: 10.1016/j.humov.2014.10.001

Bergmann, J., Kumpulainen, S., Avela, J., and Gruber, M. (2013). Acute effects of motor imagery on performance and neuromuscular control in maximal drop jumps. *J. Imagery Res. Sport Phys. Activity* 8, 45–53. doi: 10.1515/jirspa-2013-0001

Chye, S., Valappil, A. C., Wright, D. J., Frank, C., Shearer, D. A., and Tyler, C. J. (2022). The effects of combined action observation and motor imagery on corticospinal excitability and movement outcomes: two meta-analyses. *Neurosci. Biobehav. Rev.* 143:104911. doi: 10.1016/j.neubiorev.2022.104911

Cohen, J. (2013). *Statistical Power Analysis for the Behavioral Sciences*. Milton Park: Routledge.

Collet, C., Guillot, A., Lebon, F., MacIntyre, T., and Moran, A. (2011). Measuring motor imagery using psychometric, behavioral, and psychophysiological tools. *Exerc. Sport Sci. Rev.* 39, 85–92. doi: 10.1097/JES.0b013e31820ac5e0

Del Percio, C., Rossini, P. M., Marzano, N., Iacoboni, M., Infarinato, F., Aschieri, P., et al. (2008). Is there a "neural efficiency" in athletes? a high-resolution EEG study. *Neuroimage* 42, 1544–1553. doi: 10.1016/j.neuroimage.2008.05.061

Di Rienzo, F., Blache, Y., Kanthack, T., Monteil, K., Collet, C., and Guillot, A. (2015). Short-term effects of integrated motor imagery practice on muscle activation and force performance. *Neuroscience* 305, 146–156. doi: 10.1016/j.neuroscience.2015.07.080

Di Rienzo, F., Joassy, P., Kanthack, T., MacIntyre, T. E., Debarnot, U., Blache, Y., et al. (2019). Effects of action observation and action observation combined with motor imagery on maximal isometric strength. *Neuroscience* 418, 82–95. doi: 10.1016/j.neuroscience.2019.08.025

Eaves, D. L., Behmer, L., and Vogt, S. (2016a). EEG and behavioural correlates of different forms of motor imagery during action observation in rhythmical actions. *Brain Cogn.* 106, 90–103. doi: 10.1016/j.bandc.2016.04.013

Eaves, D. L., Riach, M., Holmes, P. S., and Wright, D. J. (2016b). Motor imagery during action observation: a brief review of evidence, theory and future research opportunities. *Front. Neurosci.* 10:514. doi: 10.3389/fnins.2016.00514

Frank, C., Wright, D. J., and Holmes, P. S. (2020). "Mental simulation and neurocognition: advances for motor imagery and action observation training in sport," in *The Routledge International Encyclopedia of Sport and Exercise Psychology*, eds D. Hackfort and R. Schinke (Milton Park: Routledge), 411–428.

Glatthorn, J. F., Gouge, S., Nussbaumer, S., Stauffacher, S., Impellizzeri, F. M., and Maffiuletti, N. A. (2011). Validity and reliability of Optojump photoelectric cells for estimating vertical jump height. *J. Strength Conditioning Res.* 25, 556–560. doi: 10.1519/JSC.0b013e3181ccb18d

Goodwin, K. A., and Goodwin, C. J. (2016). *Research in Psychology: Methods and Design*. Hoboken, NJ: John Wiley & Sons.

Gorostiaga, E., Izquierdo, M., Ruesta, M., Iribarren, J., Gonzalez-Badillo, J., and Ibanez, J. (2004). Strength training effects on physical performance and serum hormones in young soccer players. *Eur. J. Appl. Physiol.* 91, 698–707. doi: 10.1007/s00421-003-1032-y

Hardwick, R. M., Caspers, S., Eickhoff, S. B., and Swinnen, S. P. (2018). Neural correlates of action: comparing meta-analyses of imagery, observation, and execution. *Neurosci. Biobehav. Rev.* 94, 31–44. doi: 10.1016/j.neubiorev.2018.08.003

Hars, M., and Calmels, C. (2007). Observation of elite gymnastic performance: processes and perceived functions of observation. *Psychol. Sport Exerc.* 8, 337–354. doi: 10.1016/j.psychsport.2006.06.004

Hétu, S., Grégoire, M., Saimpont, A., Coll, M.-P., Eugène, F., Michon, P.-E., et al. (2013). The neural network of motor imagery: an ALE meta-analysis. *Neurosci. Biobehav. Rev.* 37, 930–949. doi: 10.1016/j.neubiorev.2013.03.017

Holmes, P., and Calmels, C. (2008). A neuroscientific review of imagery and observation use in sport. *J. Motor Behav.* 40, 433–445. doi: 10.3200/JMBR.40.5.433-445

Iacono, A. D., Ashcroft, K., and Zubac, D. (2021). Ain't just imagination! effects of motor imagery training on strength and power performance of athletes during detraining. *Med. Sci. Sports Exerc.* 53, 2324–2332. doi: 10.1249/MSS.0000000000002706

İnce, İ (2019). Haltercilerde bir alan testi yaklaşımı olarak dikey sıçrama güç kestirimleri ile performans arasındaki ilişkilerin incelenmesi. *Sportmetre Beden Eğitimi ve Spor Bilimleri Dergisi* 17, 48–57. doi: 10.33689/spormetre.529241

Jeannerod, M. (1994). The representing brain: neural correlates of motor intention and imagery. *Behav. Brain Sci.* 17, 187–201. doi: 10.1017/S0140525X00034026

Jeannerod, M. (2001). Neural simulation of action: a unifying mechanism for motor cognition. *Neuroimage* 14, S103–S109. doi: 10.1006/nimg.2001.0832

Jeannerod, M. (2004). Actions from within. *Int. J. Sport Exerc. Psychol.* 2, 376–402. doi: 10.1080/1612197X.2004.9671752

Jeannerod, M. (2006). *Motor Cognition: What Actions Tell the Self*, Vol. 42. Oxford: OUP Oxford.

Kim, T., Frank, C., and Schack, T. (2017). A systematic investigation of the effect of action observation training and motor imagery training on the development of mental representation structure and skill performance. *Front. Hum. Neurosci.* 11:499. doi: 10.3389/fnhum.2017.00499

Koo, T. K., and Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J. Chiropr. Med.* 15, 155–163. doi: 10.1016/j.jcm.2016.02.012

Kraeutner, S. N., McWhinney, S. R., Solomon, J. P., Dithurbide, L., and Boe, S. G. (2018). Experience modulates motor imagery-based brain activity. *Eur. J. Neurosci.* 47, 1221–1229. doi: 10.1111/ejn.13900

Kraeutner, S. N., Stratas, A., McArthur, J. L., Helmick, C. A., Westwood, D. A., and Boe, S. G. (2020). Neural and behavioral outcomes differ following equivalent bouts of motor imagery or physical practice. *J. Cogn. Neurosci.* 32, 1590–1606. doi: 10.1162/jocn_a_01575

Lang, W., Beisteiner, R., Lindinger, G., and Deecke, L. (1992). Changes of cortical activity when executing learned motor sequences. *Exp. Brain Res.* 89, 435–440. doi: 10.1007/BF00228259

Lee, J., Kraeutner, S. N., Pancura, D. R., and Boe, S. G. (2021). Probing the effect of block duration on corticospinal excitability during motor imagery performance. *J. Motor Behav.* 53, 316–323. doi: 10.1080/00222895.2020.1774491

Lindsay, R. S., Larkin, P., Kittel, A., and Spittle, M. (2023). Mental imagery training programs for developing sport-specific motor skills: a systematic review and meta-analysis. *Phys. Educ. Sport Pedagogy* 28, 444–465. doi: 10.1080/17408989.2021.1991297

Markovic, G., Dizdar, D., Jukic, I., and Cardinale, M. (2004). Reliability and factorial validity of squat and countermovement jump tests. *J. Strength Conditioning Res.* 18, 551–555. doi: 10.1519/00124278-200408000-00028

Meers, R., Nuttall, H., and Vogt, S. (2020). Motor imagery alone drives corticospinal excitability during concurrent action observation and motor imagery. *Cortex* 126, 322–333. doi: 10.1016/j.cortex.2020.01.012

Mikkola, J. S., Rusko, H. K., Nummela, A. T., Paavolainen, L. M., and Häkkinen, K. (2007). Concurrent endurance and explosive type strength training increases activation and fast force production of leg extensor muscles in endurance athletes. *J. Strength Conditioning Res.* 21:613. doi: 10.1519/R-20045.1

Monsma, E. V., Short, S. E., Hall, C. R., Gregg, M., and Sullivan, P. (2009). Psychometric properties of the revised movement Imagery Questionnaire (MIQ-R). *J. Imagery Res. Sport Phys. Activity* 4, doi: 10.2202/1932-0191.1027

Mulder, T., Zijlstra, S., Zijlstra, W., and Hochstenbach, J. (2004). The role of motor imagery in learning a totally novel movement. *Exp. Brain Res.* 154, 211–217. doi: 10.1007/s00221-003-1647-6

Nedelko, V., Hassa, T., Hamzei, F., Schoenfeld, M. A., and Dettmers, C. (2012). Action imagery combined with action observation activates more corticomotor regions than action observation alone. *J. Neurol. Phys. Therapy* 36, 182–188. doi: 10.1097/NPT.0b013e318272cad1

O'Shea, H., and Moran, A. (2017). Does motor simulation theory explain the cognitive mechanisms underlying motor imagery? a critical review. *Front. Hum. Neurosci.* 11:72. doi: 10.3389/fnhum.2017.00072

Olsson, C. J., and Nyberg, L. (2010). Motor imagery: if you can't do it, you won't think it. *Scand. J. Med. Sci. Sports* 20, 711–715. doi: 10.1111/j.1600-0838.2010.01101.x

Olsson, C. J., Jonsson, B., and Nyberg, L. (2008). Internal imagery training in active high jumpers. *Scand. J. Psychol.* 49, 133–140. doi: 10.1111/j.1467-9450.2008.00625.x

Passer, M. (2020). *Research Methods: Concepts and Connections*. New York, NY: Macmillan Higher Education.

Paulo Manochio, J., Lattari, E., Matta Mello, Portugal, E., Sobral Monteiro-Junior, R., Paes, F., et al. (2015). From mind to body: is mental practice effective on strength gains? a meta-analysis. *CNS Neurol. Disorders-Drug Targets* 14, 1145–1151. doi: 10.2174/1871527315666151111125847

Ranganathan, V. K., Siemionow, V., Liu, J. Z., Sahgal, V., and Yue, G. H. (2004). From mental power to muscle power—gaining strength by using the mind. *Neuropsychologia* 42, 944–956. doi: 10.1016/j.neuropsychologia.2003.11.018

Richard Ridderinkhof, K., Forstmann, B. U., Wylie, S. A., Burle, B., and van den Wildenberg, W. P. (2011). Neurocognitive mechanisms of action control: resisting the call of the Sirens. *Wiley Interdisciplinary Rev. Cogn. Sci.* 2, 174–192. doi: 10.1002/wcs.99

Rizzolatti, G., and Craighero, L. (2010). Premotor theory of attention. *Scholarpedia* 5:6311. doi: 10.4249/scholarpedia.6311

Romano-Smith, S., Wood, G., Wright, D., and Wakefield, C. (2018). Simultaneous and alternate action observation and motor imagery combinations improve aiming performance. *Psychol. Sport Exerc.* 38, 100–106. doi: 10.1016/j.psychsport.2018.06.003

Schack, T. (2004). The cognitive architecture of complex movement. *Int. j. sport. and exercise psy.* 2, 403–438. doi: 10.1080/1612197X.2004.9671753

Simonsmeier, B. A., Andronie, M., Buecker, S., and Frank, C. (2021). The effects of imagery interventions in sports: a meta-analysis. *Int. Rev. Sport Exerc. Psychol.* 14, 186–207. doi: 10.1080/1750984X.2020.1780627

Smith, D., and Holmes, P. (2004). The effect of imagery modality on golf putting performance. *J. Sport Exerc. Psychol.* 26, 385–395. doi: 10.1123/jsep.26.3.385

Smith, D., Romano-Smith, S., Wright, D. J., Deller-Rust, B., and Wakefield, C. J. (2020). The effects of combining PETTLEP imagery and action observation on bicep strength: a single-case design. *J. Appl. Sport Psychol.* 32, 377–391. doi: 10.1080/10413200.2018.1560372

Ste-Marie, D. M., Law, B., Rymal, A. M., Jenny, O., Hall, C., and McCullagh, P. (2012). Observation interventions for motor skill learning and performance: an applied model for the use of observation. *Int. Rev. Sport Exerc. Psychol.* 5, 145–176. doi: 10.1080/1750984X.2012.665076

Toth, A. J., McNeill, E., Hayes, K., Moran, A. P., and Campbell, M. (2020). Does mental practice still enhance performance? a 24 Year follow-up and meta-analytic replication and extension. *Psychol. Sport Exerc.* 48:101672. doi: 10.1016/j.psychsport.2020.101672

Vogt, S., Di Rienzo, F., Collet, C., Collins, A., and Guillot, A. (2013). Multiple roles of motor imagery during action observation. *Front. Hum Neurosci.* 7:807. doi: 10.3389/fnhum.2013.00807

Wakefield, C. J., and Smith, D. (2009). Impact of differing frequencies of PETTLEP imagery on netball shooting performance. *J. Imagery Res. Sport Phys. Activity* 4, 1–12. doi: 10.2202/1932-0191.1043

Wakefield, C., Smith, D., Moran, A. P., and Holmes, P. (2013). Functional equivalence or behavioural matching? A critical reflection on 15 years of research using the PETTLEP model of motor imagery. *Int. Rev. Sport Exerc. Psychol.* 6, 105–121. doi: 10.1080/1750984X.2012.724437

Walsh, M., Arampatzis, A., Schade, F., and Brüggemann, G.-P. (2004). The effect of drop jump starting height and contact time on power, work performed, and moment of force. *J. Strength Conditioning Res.* 18, 561–566.

Williams, S. E., Cooley, S. J., and Cumming, J. (2013). Layered stimulus response training improves motor imagery ability and movement execution. *J. Sport Exerc. Psychol.* 35, 60–71. doi: 10.1123/jsep.35.1.60

Wright, C. J., and Smith, D. (2009). The effect of PETTLEP imagery on strength performance. *Int. J Sport Exerc. Psychol.* 7, 18–31. doi: 10.1080/1612197X.2009.9671890

Wright, D. J., Frank, C., and Bruton, A. M. (2022). Recommendations for combining action observation and motor imagery interventions in sport. *J. Sport Psychol. Action* 13, 155–167. doi: 10.1080/21520704.2021.1971810

Wright, D. J., Wood, G., Eaves, D. L., Bruton, A. M., Frank, C., and Franklin, Z. C. (2018). Corticospinal excitability is facilitated by combined action observation and motor imagery of a basketball free throw. *Psychol. Sport Exerc.* 39, 114–121.

Young, W. B., Pryor, J. F., and Wilson, G. J. (1995). Effect of instructions on characteristics of countermovement and drop jump performance. *J. Strength Conditioning Res.* 9, 232–236. doi: 10.1519/00124278-199511000-00005

Yue, G., and Cole, K. J. (1992). Strength increases from the motor program: comparison of training with maximal voluntary and imagined muscle contractions. *J. Neurophysiol.* 67, 1114–1123. doi: 10.1152/jn.1992.67.5.1114

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 15 July 2024
DOI 10.3389/fpsyg.2024.1357312

Check for updates

OPEN ACCESS

EDITED BY
Sergio Machado,
Federal University of Santa Maria, Brazil

REVIEWED BY
Thomas Muehlbauer,
University of Duisburg-Essen, Germany
Morteza Taheri,
University of Tehran, Iran

*CORRESPONDENCE
Karen Zentgraf
✉ zentgraf@sport.uni-frankfurt.de

RECEIVED 17 December 2023
ACCEPTED 25 June 2024
PUBLISHED 15 July 2024

CITATION
Brinkbäumer M, Kupper C, Reichert L and Zentgraf K (2024) Dual-task costs in speed tasks: a comparison between elite ice hockey, open-skill and closed-skill sports athletes. *Front. Psychol.* 15:1357312.
doi: 10.3389/fpsyg.2024.1357312

Dual-task costs in speed tasks: a comparison between elite ice hockey, open-skill and closed-skill sports athletes

Mark Brinkbäumer, Christian Kupper, Lukas Reichert and Karen Zentgraf*

Department of Movement and Exercise Science, Institute for Sport Sciences, Goethe University, Frankfurt, Germany

Introduction: Ice hockey is a high pace sports game that requires players to integrate multiple skills. Players face perceptive, cognitive, and motor tasks concurrently; hence, players are regularly exposed to dual- or multi-task demands. Dual-tasking has been shown to lead to decreased performance in one or both performed tasks. The degree of performance reductions might be modulated by the exhaustion of cognitive resources. Literature on dual-task paradigms that combine sport-relevant elements is scarce. Therefore, a novel paradigm combining cyclical speed of the lower extremities and concurrent visuo-verbal speed reading was tested and validated. Additionally, to understand the nature of dual-task costs, the relationship between these costs and cognitive performance was assessed. We hypothesized occurrence of dual-task costs in all athletes without relationship to single task performance. Differences in dual-task cost were expected between open-skill and closed-skill sports, as well as differing expertise levels. Level of cognitive function was expected to explain some variance in dual-task cost.

Methods: A total of 322 elite athletes (120 ice hockey, 165 other team sports, 37 closed-skill sports) participated in this study. Each athlete performed a tapping task, a visuo-verbal speed-reading task, and both tasks simultaneously. All ice hockey athletes performed additional cognitive tests assessing processing speed, spatial working memory, sustained attention, two choice reaction time, and motor inhibition.

Results: The results of paired-sample t-tests confirmed significant dual-task costs for all sport groups ($p < 0.001$). Single-task performance and dual-task costs correlated weakly in a positive direction. A one-way ANOVA revealed significantly greater costs in closed-skill sports athletes than in ice hockey and other sports athletes. No significant differences in dual-task costs were found between teams of differing expertise levels. Lastly, no significant regression model was found to predict dual-task costs from cognitive test performance.

Discussion: Our study suggests that this novel dual-task paradigm was successful in inducing dual-task costs for all elite athletes. Since it distinguishes between closed-skill and open-skill sports athletes, it might be a valuable diagnostic tool for performance and for talent development of open-skill athletes. Dual-task costs could not be relevantly predicted via cognitive performance measures, questioning cognitive resource theories as an explanation for dual-task costs.

KEYWORDS

dual-task, dual-task cost, cognitive-motor interference, elite athletes, high performance

1 Introduction

Ice hockey is a high-pace contact sports game in which players perform repeated bouts of high-intensity action. Players are rotated in shifts of 30–80 s over four quarters of 15 min (Burr et al., 2008; Bond et al., 2018; Vigh-Larsen et al., 2019). During the entire game, players are in action on ice for 15–25 min (Roczniok et al., 2016). Players must be physically fast and well-conditioned for a wide range of ice hockey actions, such as cuts, turns, weave agility, decelerations, accelerations, and collisions (Novák et al., 2019). Especially considering the evolution of the game towards increased game speed (Westerlund and Summanen, 2001; Thomas, 2006), there seems to be a striking need for fast players. A nine-year trend study by Bielmann et al. (2022) provides evidence that players are indeed improving their physical speed, at least in their sample of male U18 Swiss national ice hockey players. Moreover, successful performance requires the players to integrate multiple skills from different domains, i.e., locomotion while passing or shooting (Fait et al., 2011). This integration in game-like behaviour has substantial information processing demands, especially on the perceptual and cognitive side (Broadbent et al., 2014).

In the increasingly dynamic field of modern sports, the interplay of physical and cognitive abilities seems to be essential (Ghasemzadeh and Saadat, 2023). For optimal performance, both seem to be intricately connected (Navabinejad and Rostami, 2023). Perceptual-cognitive function and skill are factors associated with superior sport performance (Scharfen and Memmert, 2019). Cognitive performance can be distinguished into domain-specific skills or domain-general functions (Kalén et al., 2021). The "expert performance approach" (Ericsson, 2003) has consistently shown that experts outperform novices on domain-specific tests that require visual scanning, prediction, spatial memory, and decision making (Janelle and Hillman, 2003; Mann et al., 2007). Though domain-specific tests are ecologically valid and can shed some light on differences between athletes of varying expertise levels (Ericsson, 2003), test results are heavily influenced by athletes' procedural and declarative knowledge (Voss et al., 2010). This makes comparisons across sports hardly possible (Vestberg et al., 2012). The "cognitive component approach" assesses domain-general functions (Voss et al., 2010). Several studies found that players with greater expertise show superior performance in cognitive functions such as processing speed (Chaddock et al., 2011), working memory (Vaughan and Laborde, 2021), hand and foot motor inhibition (Heppe and Zentgraf, 2019), multiple object tracking (MOT) (Qiu et al., 2018), executive functions (Vestberg et al., 2012; Verburgh et al., 2014) and attention (Moratal et al., 2020) compared to less experienced players. Domain-general assessment allows comparisons across different sports (Mann et al., 2007; Voss et al., 2010; Wang et al., 2013; Krenn et al., 2018; Formenti et al., 2021; Koch and Krenn, 2021; Heilmann et al., 2022). According to their cognitive-perceptual demands, sports can be classified into open-skill and closed-skill sports (Wang et al., 2013; Gu et al., 2019; Zhu et al., 2020; Formenti et al., 2021; Koch and Krenn, 2021; Yongtawee et al., 2021; Heilmann et al., 2022). Open-skill sports take place in a dynamic environment, where athletes are externally paced and must constantly adjust to teammates and opponents. Ice hockey would be an example of open-skill sport. Closed-skill sports are more predictable and routine, allowing a greater extent of internal pacing by the participating athletes. Gymnastics is an example of closed-skill sport. In a meta-analysis, Zhu et al. (2020) found that closed-skill sport athletes show inferior performance in executive functions compared to open-skill sport athletes, when looking at cross-sectional studies. Data from interventional studies does, however, not support the advantage of open-skill sport for executive functions (Zhu et al., 2020).

There is little work on cognitive abilities of ice hockey players. In Faubert and Sidebottom (2012) discussed an approach to practice high-level athletes' perceptual-cognitive skills via a three-dimensional MOT system. Several professional team sport athletes, including players from two National Hockey League (NHL) teams, were part of the sample. All professional players increased their perceptual-cognitive performance in the MOT task with training, with no differences between sports. The position in which players completed the test however seemed to influence the performance. One NHL team, which performed the test standing, performed worse than all other teams tested sitting.

Zhang et al. (2021) investigated the relationship between brain activity and attentional performance in a MOT-test among ice-hockey players. They found that elite players outperformed intermediate players in tracking accuracy and demonstrated higher individual alpha peak frequency, an electroencephalogram variable associated with attention and working memory. Furthermore, Lundgren et al. (2016) compared elite ice hockey players to a standardized sample consisting of 1750 nonclinical individuals ranging in age from 8 to 89 years. They found that the athletes scored significantly higher on design fluency, a measure of executive function from the Delis-Kaplan Executive Function System battery (Baldo et al., 2001; Delis et al., 2001). Additionally, they report a robust correlation between on-ice performance and trail making test scores, however, no differences between higher-and lower-league players were found. Lastly, James (2023) investigated the differences in executive functions between different divisions of Swedish ice hockey players. Coherent with Lundgren et al. (2016), no differences between divisions were found for inhibition and updating. Unexpectedly, shifting favoured lower division athletes. In general, more research on cognitive abilities of ice hockey athletes is needed.

Since team sport athletes in general face motor and perceptual-cognitive demands simultaneously, they are regularly exposed to dual-or multitasking scenarios (Moreira et al., 2021). Multitasking can be defined as the timely overlap of cognitive and motor processes when performing two (or more) tasks (Koch et al., 2018). This is typically accompanied by a decrease in performance of one or more tasks (dual−/multi-task cost) (Beurskens et al., 2015, 2016a,b; Plummer et al., 2015; Belghali et al., 2017; Solomito et al., 2018). In their review, Moreira et al. (2021) found that despite regularly being exposed to time-constrained situations and multitasking, athletes showed acute motor and cognitive performance costs in dual-task (DT) situations. In one of the included studies, Qiu et al. (2018) investigated the effect of varying expertise levels of basketball players on MOT task performance and found that experts demonstrated better performance than amateurs, who in turn performed better than novices. These results are in line with the results of Amico and Schaefer (2022) who found that experts outperformed intermediate tennis players. This suggests that superior DT performance can be an indicator of skill level in open-skill sports. Regarding the aetiology of performance costs, Moreira et al. (2021) discuss that high working memory capacity could be a resource that enables superior DT performance. Additionally, Fleddermann et al. (2019) found that chronic DT exposure leads to improvements in measures of processing speed and sustained attention. Casella et al. (2022) also reported improvement in all measures of cognitive functioning and attention capacity after performing 10 weeks of cognitive-motor DT training in young soccer players. This highlights a possible relationship between cognitive abilities and executive functions and DT performance, yet the direction of impact is unclear.

In social and cognitive psychology, a lot of research has been performed on the topic of dual−/multi-tasking and plenty of theories try to explain the underlying processes (Koch et al., 2018). Early studies conceptualize information processing as structurally limited to a "single channel" (Broadbent, 1958). According to this view, it is not possible for two channels to be processed simultaneously. This processing bottleneck, all-or-nothing perspective or attention "filter" requires fast channel switching in a DT setting (Lachter et al., 2004). This account specifically relates to early processing steps of perception (Broadbent, 1958). According to Kahneman (1973), DT costs (DTC) can be ascribed to the division of attention, which he theorized to be a limited central processing resource. This division of attention concept fits nicely to the concept of graded sharing of a central resource, postulated by Pashler (1998). Pashler (1994) further states there is no central bottleneck on the perceptual level, but rather in response selection. Current evidence that shows shared coding processes of perception and action opposes this view and questions the sequential nature of information processing (Fischer and Plessow, 2015). However, the assumption of sequential information processing, especially with the locus-of-slack-logic seems to be a useful heuristic that advanced research in the area (Koch et al., 2018). Fischer and Plessow (2015) describe the response selection bottleneck as context-sensitive, optimizing for performance. Presumably, multitasking requires maintenance of a balance between minimizing between-task interference, by serial task processing, and minimizing mental effort, by allowing for more parallel processing. Navon (1984) advanced the concept of a central resource and stated that there is not one, but multiple, domain-specific resources. Wickens (2008) proposes a multiple resource theory with four dimensions: (1) stages of processing distinguish between perceptual and cognitive tasks and selection and execution of action. (2) codes of processing differentiate between spatial activity and verbal/linguistic activity. This dimension is expressed in perception, working memory and action. (3) modalities (of perception), recognizes different resources for auditory and visual perception. (4) visual channels indicate a difference between focal and ambient vision within visual resources. If two tasks draw from distinct resources, less performance losses are to be expected. Assuming a domain-general resource that is shared by all tasks, at least one of the tasks must suffer from decreased performance when they overlap temporally. Several studies seem to confirm that when a visual-manual and an auditory-vocal ask are performed concurrently, there are smaller costs than when an auditory-vocal and auditory-manual task are performed at the same time (Hazeltine et al., 2006; Stelzel et al., 2006; Göthe et al., 2016). These findings are in line with Wickens (2008) since the latter combination of tasks should produce overlap in the perceptual-auditory resource.

Wollesen et al. (2022) discuss an increase in DT efficiency through greater task automatization as a possible adaptation to DT exposure. Hence, it may be important to test cognitive-motor interference in paradigms that are similar and specific to the sport, regarding both motor and cognitive demands. However, only five of the studies included in the review of Moreira et al. (2021) had a sport-specific paradigm (Helm et al., 2016; Gutiérrez-Davila et al., 2017; Fleddermann et al., 2019; Laurin and Finez, 2020; Schaefer and Scornaienchi, 2020). One very important physical feature that is recurring in many team sports is rapid locomotion, i.e., speed of movement (Brown and Ferrigno, 2015). Hence, it could be promising to examine DT performance with a motor task focusing on speed. The lower-body tapping task has been employed to assess cyclical speed of athletes (Chaabouni et al., 2022) and might be an option as an easily implemented and sufficiently specific motor task for team sports. On the cognitive side, next to perception, communication seems to be a crucial aspect of sports (Ishak, 2017). Especially verbal communication seems to be important to give teammates increased opportunity to notice and act upon events in the complex, fast-paced, highly contingent environment of actual play (LeCouteur and Feo, 2011). Players must quickly recognize observed scenarios and verbalize them to teammates to aid in his/her own perception.

In summary, ice hockey, like other team sports, has high cognitive and motor demands, which occur simultaneously in a match. Concurrent cognitive and motor tasks usually result in performance decrements or cognitive-motor interference. Superior ability to handle these kinds of scenarios might distinguish experts from less skilled players. Nevertheless, empirical findings show that even elite athletes demonstrate decreased performance under DT scenarios. Possible explanations for this phenomenon might be underlying cognitive resources, lacking automatization of motor skill or an interference between the representations engaged by central operations. Research on DT paradigms focusing on speed in athletes is lacking, hence a novel paradigm involving a lower-body tapping task and visuo-verbal speed-reading task is proposed.

The aim of this study is to (1) test a new DT paradigm focusing on cyclical speed of the lower extremities and concurrent visuo-verbal speed reading in ice hockey players, (2) check if DTC arise independently of ST performance, (3) validate it against other open-skill and closed-skill sports (4) compare performance between different teams/age groups, (5) assess the relationship between DT performance and cognitive functions, to potentially identify underlying resources. The working hypotheses of this study are (1) the employed paradigm will be demanding enough to provoke significant performance costs in elite ice hockey players and other elite athletes, (2) DTC will not be correlated to ST performance, (3) there will be no differences in DTC between ice hockey players and other open-skill sports athletes, but closed-skill sports athletes will display significantly greater costs than both groups, (4) more experienced players will display less DTC than less experienced (men's U20 < men's U18 & women's first team < women's U18), (5) if DTC rely on cognitive resources, there should be a relationship between measures of cognitive functions and DTC.

2 Materials and methods

2.1 Subjects

The data was gathered during two projects by the German Federal Institute for Sport Science. Testing of the athletes ensued in the context of extensive performance diagnostics, which was performed during German national team training camps (with the exemption of the handball players). A total of 322 elite athletes participated. All

10.3389/fpsyg.2024.1357312

confirmed mental and physical readiness and signed a consent form before participating. Only athletes with healthy vision or correction (glasses or contact lenses) were allowed to participate. One-hundred and twenty ice hockey athletes of the German national team ($w = 40$, $m = 79$), aged 18.66 ± 3.91 years, participated. Players were part of women's A (first) team ($n = 18$), women's U18 ($n = 22$), men's U20 ($n = 36$) and men's U18 ($n = 44$). Furthermore, 165 elite team sport athletes were part of the performance diagnostics. Seventy-one were volleyball athletes of the German national team ($w = 32$, $m = 39$), aged 20.02 ± 5.02 years, 68 were basketball athletes of the German 3 × 3 and 5 versus 5 national team ($w = 29$, $m = 39$), with an average age of 21.67 ± 4.66 years, 15 were male handball players of the highest German league, aged 22.67 ± 3.16 years and 12 ($w = 5$, $m = 7$) were table tennis players from the German national team, aged 28.10 ± 6.51 years. Lastly, 37 athletes from closed sports took part. Eleven were modern pentathletes from the German national team ($w = 9$, $m = 2$), aged 23.78 ± 5.53 years, and 28 were trampoline gymnasts from the German national team ($w = 12$, $m = 14$), aged 18.58 ± 4.18 years.

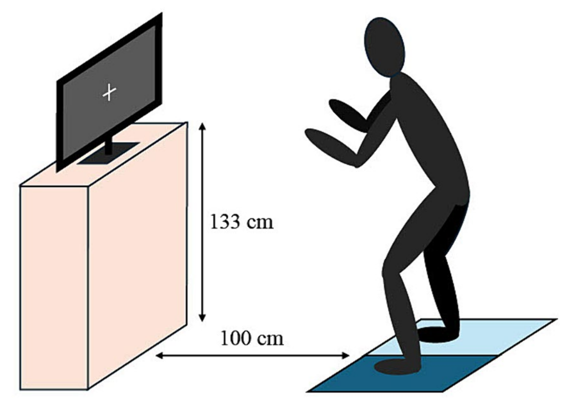


FIGURE 1
The experimental setup of the dual-task test paradigm.

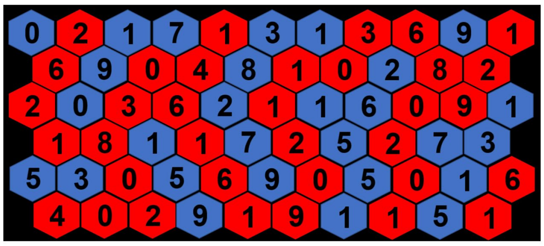


FIGURE 2
Exemplary visual speed-reading stimuli.

2.2 Procedure

All participants performed the following DT paradigm, which consisted of a motor single task (ST), cognitive ST, and a DT, which combined both ST. All subjects started with the motor ST, proceeded with the cognitive ST and finished with both at the same time as the DT. The experimental setup is illustrated in Figure 1. Cognitive tests were performed prior to DT testing.

2.3 Motor task

For the motor ST, tapping performance was measured via a contact mat (Sport Voss©). Subjects were instructed to alternately tap with the left and right leg onto the device as many times as possible, over a duration of 5 s. The test was started with an acoustic countdown and ended with final acoustic signal. Subjects started out of a standardized position with both feet on the mat with the knees slightly bent in a slight forward-leaning position. The arms were in front of the body and kept in position. The main parameter used was the maximal frequency (in Hz) of tapping, which was calculated as the highest frequency within 1 s at any time point. During the execution of the motor task, subjects were asked to keep the gaze on a cross ("+") at a screen in front of them. The screen (Samsung, SyncMaster 2,494 HS, Suwon, South Korea) was positioned 100 cm in front of the contact mat at a height of 133 cm. This visual fixation was chosen to control the focus of visual attention across the ST and DT conditions. After performing a test trial, subjects performed two trials and an additional third if the discrepancy between trials was greater than 10%.

2.4 Cognitive task

For the cognitive ST, subjects were instructed to stand on top of the contact mat in the same position as during the motor task. The acoustic start signal remained the same as in the motor task. Simultaneously to the start signal, subjects were presented with a honeycomb structure on the screen in front of them (Figure 2). Six rows with ten to eleven combs (a total of 63 combs) were presented. Every comb had a number between one and nine. Twenty-eight combs were colored in blue and the remaining in red. The stimuli were created and presented via Power Point (Microsoft, Washington, United States). Subjects had to read all numbers in blue combs as fast as possible, from left to right, top to bottom. Measurement stopped after all numbers were read. To ensure that subjects performed the cognitive task, the verbal answers were recorded using a recording mobile app. Reading time (in seconds) as well as errors were evaluated afterwards. Following a practice trial, subjects performed two trials.

2.5 Dual-task

In the DT condition, both tasks were performed simultaneously. The measurement started with the same acoustic signal as the ST. Subjects were instructed to tap as fast as possible while reading as fast and accurate as possible. They were explicitly told that both tasks were of the same importance, to minimize prioritization of any task. In contrast to the single motor task, tapping was not ended with an acoustic signal, but continued until all numbers were read. After performing a test trial, subjects performed two trials and an additional third if the discrepancy between trials was greater than 10% for the motor performance. Additionally, motor DTC was calculated as the difference between DT and ST performance.

2.6 Cognitive testing

Processing speed, sustained attention, spatial working memory, and motor inhibition performance was measured. Processing speed was assessed by the "Zahlen-Verbindungs-Test" (ZVT) (Oswald and Roth, 1987). In this paper-and-pencil test, participants must connect as many numbers as possible from 1 to 90 in the correct order within a time frame of 30 s. Overall, the test consisted of four test sheets. The dependent variable was the arithmetic mean of the accomplished items in the four sheets. The more numbers were connected correctly, the better the performance. The test was performed in the group test version according to the test manual (Oswald, 2016). The test has been shown to be a useful test with sufficient test reliability and validity (Rost and Hanses, 1993).

Sustained attention was measured by the d2-R test (Brickenkamp et al., 2010). This paper-and-pencil test measures attention and concentration ability under time pressure. The test consists of 14 lines with 47 characters per line with a randomized order of the letters "d" and "p." Each letter is equipped with one, two, three, or four vertical stripes below or above the letter. The task of the participants is to mark the letter "d" with two stripes. All other characters are distractors, and participants are supposed to ignore these characters. For each line, participants have 20 s, and there is no break between the lines. The dependent variable is concentration performance (CP), which is calculated from the processed target objects and the errors. The higher the score, the better the performance. The test execution was performed in accordance with the test manual (Brickenkamp et al., 2010). Quality criteria for the d2-R test have been shown to be to be sufficiently met (Antretter et al., 2013).

Spatial working memory was measured using the forward and backward Corsi block test (CBT) (Schellig, 2011). This test has been established as a measure of spatial memory in both clinical and research contexts for several decades (Farrell Pagulayan et al., 2006). Testing ensued in isolation, individually on a laptop (Lenovo ThinkPad L460, Hongkong) using a CBT script, programmed on PsyToolkit (Stoet, 2010, 2017), supervised by a researcher. In the forward CBT, the participants are presented with nine pink, irregularly positioned blocks on a black screen. At the beginning of the test, two of these blocks light up yellow in a specific order. The participant must remember and replicate this order, i.e., the first item must be clicked first and the last item last. If the order is clicked correctly, the number of boxes lighting up increases by one. If the order is clicked incorrectly, the same number of boxes lights up. The test ends once the order is clicked incorrectly two consecutive times. In case the participant correctly clicks all nine boxes, the test also ends. The procedure for the backward CBT was the same as for the forward CBT, but the participants must remember the order and replicate it in reverse, i.e., the last presented item must be clicked first and the last presented item must be clicked first. Average number of correctly clicked items was recorded as outcome measure. Arce and McMullen (2021) evaluated the differences between physical and digital CBT and conclude that "most evidence today suggests that they are comparable.

Motor inhibition was measured using the stop signal reaction time (SSRT) test developed by Verbruggen and Logan (2008) with the modifications first introduced by Heppe and Zentgraf (2019). Participants were faced with a go-and a stop-condition, which they completed with hands only. The go-condition was employed to determine the choice reaction time. Participants are confronted with white arrows (left or right) and must press a pad with the corresponding hand. In 25% of the trials, the stop-condition is presented. In this condition, the white arrow turns blue after a variable stop signal delay (SSD) and the participants must inhibit the planned motor response. Stimuli are presented until an answer (press on the pad) is given. An adaptive staircase procedure is used for SSD to increase or decrease the task difficulty, around the individual threshold, and produce an inhibition success rate of about 50%. This entailed a decrease of SSD if an inhibition was successful and an increase of SSD if an inhibition was failed. To measure response inhibition an integration method was used (Heppe and Zentgraf, 2019). Two-choice reaction time (2CRT) was measured in the process of determining SSRT and included as another dependent variable. The test was performed in isolation, supervised by a researcher.

2.7 Statistical analysis

Data is reported in $M \pm SD$. DTC were calculated as the difference between DT performance and ST performance. For statistical analysis SPSS Statistics Version 26 (IBM Corporation, Armonk, United States) was used. The level of significance was set at $p < 0.05$. The difference between ST and DT was assessed via paired sample t-tests to investigate the effect of performing both tasks simultaneously. In order to rule out a direct relationship between ST performance and DTC, a Pearson's correlation was performed. To investigate relationship between sport type and DTC, group differences in DTC were explored with a one-way ANOVA for sport type (ice hockey, open-skill sports and closed-skill). A one-way ANOVA for national team (women's first team, women's U18, men's U20, men's U18) was performed to assess the differences between varying expertise levels and DTC. η^2 was used as a measure of effect size. A multiple linear regression was calculated to investigate the relationship between the dependent variable DTC and the independent variables ZVT raw value, d2-R concentration performance, CBT span forward, CBT span backward, SSRT and 2CRT, in ice hockey athletes.

3 Results

3.1 Descriptive

The mean ST performance was 12.51 Hz ± 1.27 for the ice hockey athletes, 11.85 Hz ± 1.04 for the other open-skill sports athletes and 10.58 Hz ± 1.17 for closed-skill sports athletes. The mean DT performance was 11.00 Hz ± 1.39 for the ice hockey athletes, 10.57 Hz ± 1.36 for the other open-skill sports athletes and 8.53 Hz ± 1.38 for closed-skill sports athletes. This resulted in DTC of 1.51 Hz ± 1.01 [−0.82, 4.61] for ice hockey athletes, 1.30 Hz ± 0.94 [−0.77, 5.35] for the other open-skill sport athletes and 2.05 Hz ± 1.11 [0.06, 4.59] for closed-skill sport athletes. Individual ST and DT performance for ice hockey, open-skill and closed-skill sport athletes are depicted in Figure 3.

3.2 ST and DTC

The Shapiro–Wilk's test revealed normal distributions for ST and DT performance of all groups, ice hockey ST ($W = 0.988$, $p = 0.408$)

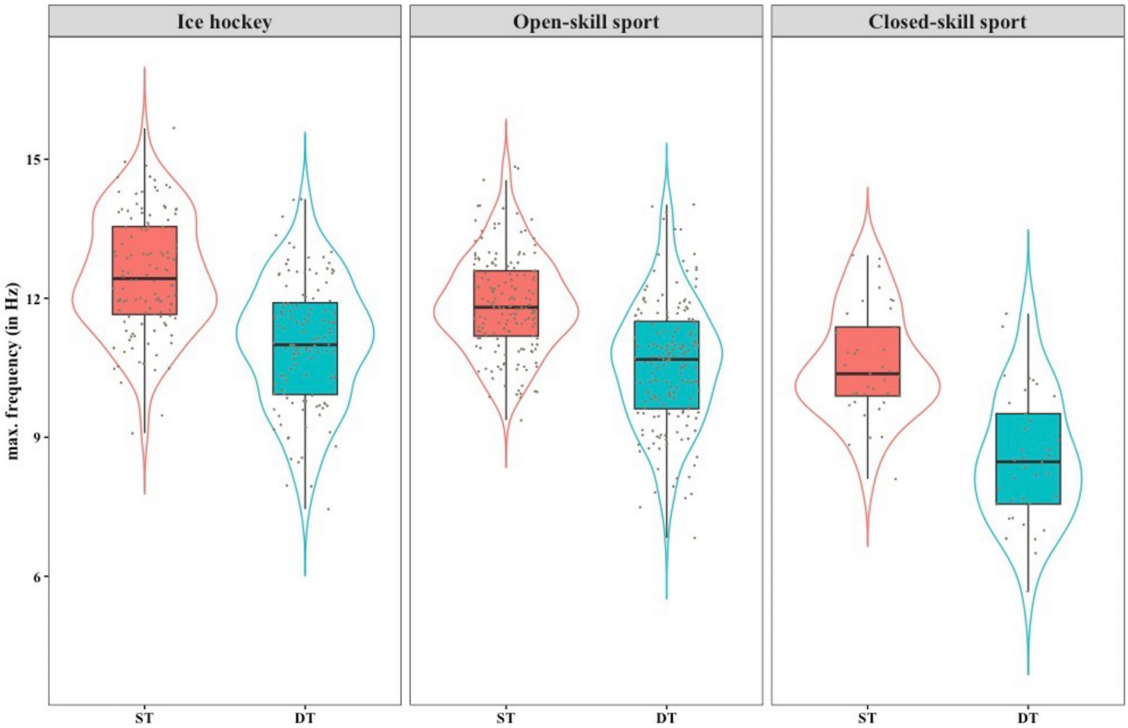


FIGURE 3
Overview of the ST and DT performance of ice hockey, open-skill and closed-skill sport athletes.

& DT ($W = 0.990$, $p = 0.503$), open-skill sports ST ($W = 0.994$, $p = 0.728$) & DT ($W = 0.994$, $p = 0.782$) and closed-skill sports ST ($W = 0.969$, $p = 0.377$) & DT ($W = 0.982$, $p = 790$). Paired sample t-tests revealed a significantly lower performance in the DT condition for ice hockey $t(119) = 16{,}367$, $p < 0.001$, open-skill sports $t(165) = 17.897$, $p < 0.001$, and closed-skill sports $t(36) = 11{,}223$, $p < 0.001$. The Shapiro Wilk's test indicated a normal distribution for ST performance ($W = 0.988$, $p = 0.408$) and DTC ($W = 0.984$, $p = 0.153$). ST and DTC were found to be significantly positively correlated $r(120) = 0.273$, $p = 0.003$.

3.3 DTC and sport types

Figure 4 illustrates the difference in DTC between sport types. The Shapiro Wilk's test confirmed normality of the data for DTC in ice hockey players ($W = 0.984$, $p = 0.153$), other open-skill sports athletes ($W = 0.99$, $p = 0.296$) and closed-skill sports athletes ($W = 0.958$, $p = 0.170$). Homogeneity of variance was confirmed, as assessed by Levene's test for equality of variances ($p = 0.443$). A box plot indicated one outlier, which was checked, but kept in the data because it was a genuine value. The test revealed statistically significant differences in DTC between groups, $F(2, 319) = 10.064$, $p < 0.001$. There was no statistically significant difference between ice hockey and open-skill sports ($p = 0.111$). However, there was a mean decrease of 0.54 Hz, 95% *CI* [0.05, 1.03] in DTC from closed-skill sports (2.05 ± 1.11 Hz) to ice hockey (1.51 ± 1.01 Hz), which was statistically significant ($p = 0.009$). A comparison of closed-skill sports to open-skill sports (1.28 ± 0.89 Hz) showed a mean decrease in DTC of 0.77 Hz 95% *CI* [0.30, 1.25], which was also statistically significant ($p < 0.001$).

3.4 DTC and expertise

Figure 5 depicts the difference in DTC between expertise levels. A Shapiro Wilk's test confirmed normality of the data for DTC in men's U20 ($W = 0.975$, $p = 0.593$), men's U18 ($W = 0.96$, $p = 0.1{,}27$), women's first team ($W = 0.957$, $p = 0.54$) and women's U18 ($W = 0.961$, $p = 0.502$). Homogeneity of variance was confirmed, as assessed by Levene's test for equality of variances ($p = 0.906$). A box plot indicated one outlier, which was checked, but kept in the data because it was a genuine value. The test did not indicate statistically significant differences between groups, $F(3{,}116) = 1.034$, $p = 0.608$.

3.5 DTC and cognitive parameters

For the regression, independence of residuals was established, as assessed by a Durbin-Watson statistic of 2.046. Homoscedasticity was confirmed by visual inspection of a plot of regression standardized residuals versus dependent variable and *VIF* values indicated no multicollinearity. Results of the regression model are depicted in Table 1.

4 Discussion

The first aim of this study was to test a novel, open-skill sport-specific DT paradigm focusing on cyclical speed of the lower extremities and concurrent visuo-verbal speed-reading task in elite athletes of diverse sporting backgrounds. Three groups were distinguished in the analysis: ice hockey, other open-skill,

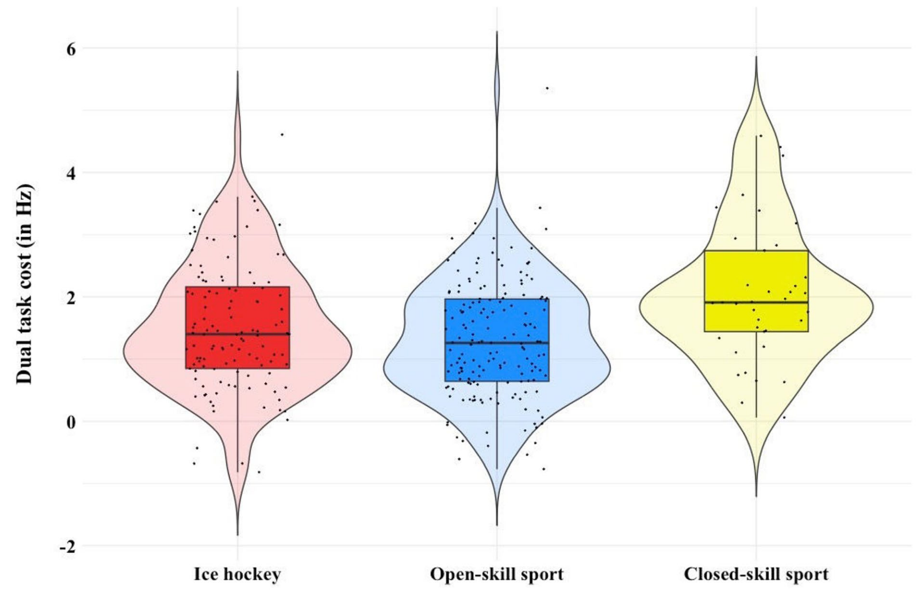


FIGURE 4
Comparison of dual-task costs between ice hockey, open-skill and closed-skill sports.

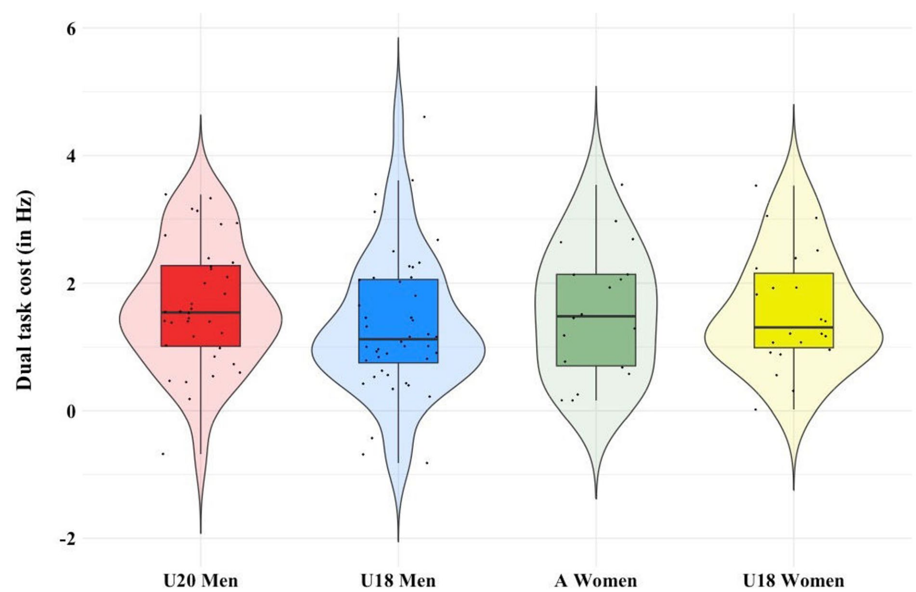


FIGURE 5
Comparison of dual task costs between ice hockey national teams.

closed-skill sport. Consistent with the results of Moreira et al. (2021), we expected all athletes to experience DTC in the paradigm. The results show significant decreases in performance from ST to DT in all three groups. The wide range in DTC highlights the heterogenous response to the DT condition. Some athletes' performance was unaffected, whereas others displayed great performance decrements. The data seems to support that the paradigm was able to induce significant DTC, hence the first hypothesis can be confirmed. These results are in line with the review of Moreira et al. (2021), who also reported acute performance decreases under DT conditions. In one of the included studies, Fleddermann et al. (2019) employed two volleyball-specific DT tests (low and high cognitive complexity) paired with 3D-MOT. In the low-complexity task, athletes performed maximal block jumps either to the left or right, reacting to a volleyball-specific static picture. The high-complexity task also entailed maximal block jumps either to the left or right, but triggered by a volleyball-specific video, which was presented on a screen in front of the net. Results confirmed that both additional tasks induced performance decrements. Performance in the high-complexity task was worse than in the low-complexity task. It is remarkable that even most elite

TABLE 1 Multiple regression model for dual-task cost and cognitive performance.

Multiple regression model		R^2 (adjusted)	*SEE* (m)		*p*-value
		0.033 (−0.039)	1.05		0.839
Variables	**ß**	**95% CI**	**B**	**T**	**p-value**
Constant		[−1.066, 6.221]	2.578	1.408	0.163
ZVT	-0,71	[−0.42, 0.025]	−0.008	−0.483	0.630
d2-R	0.016	[−0.007, 0.008]	0.000	0.120	0.905
CBT fwd.	−0.179	[−0.438, 0.081]	−0.178	−1.366	0.176
CBT bwd.	0.158	[−0.129, 0.454]	0.162	1.109	0.271
2CRT	−0.053	[−0.005, 0.003]	−0.001	−0.432	0.667
SSRT	−0.019	[−0.007, 0.006]	0.000	−0.152	0.879

SEE, standard error of estimate; β, standardized coefficient; B, unstandardized coefficient.

athletes display significant DTC in a paradigm that entails game relevant tasks, like cyclical speed of the lower body, visual perception, and verbal communication. It seems likely that athletes who display costs in this paradigm, also suffer from cognitive-motor interference in game scenarios. This might manifest in decreased speed of movement, miscommunication, or lack of communication, when cognitive and motor demands occur in parallel. Consequently, identifying the underlying causes and addressing possible weaknesses might be a promising venture to tap performance reserves.

Secondly, we wanted to check if there was a relationship between DTC and ST performance. If the DTC and ST performance were strongly correlated, one could simply discard testing of DTC and keep focus on the development of ST. However, there could be a link between both through task prioritization. Despite being instructed to not prioritize one task over the other, athletes tend to give greater priority to the motor task. Nevertheless, we expected no correlation between DTC and ST. The data analysis showed a weak positive correlation between DTC and ST. Consequently, the second hypothesis cannot be completely verified. Despite this result, we do assume sufficient independence of DTC and ST for DTC to be an important parameter to assess in athletes.

Validation of the new DT paradigm against other open-skill and closed-skill sports was the third aim of the study. Due to greater exposure to DT scenarios and the existing literature on perceptual/cognitive expertise in sports (Mann et al., 2007; Voss et al., 2010; Zhu et al., 2020), we expected differences between open-skill and closed-skill sport. Since ice hockey is an open-skill sport, differences were only expected in comparison to closed-skill sport. Furthermore, older athletes have been exposed to DT scenarios more often than younger players, hence they should show smaller performance decrements. DTC were highest in closed-skill sport, second highest in ice hockey athletes and lowest in other open-skill sports. The difference in DTC between ice hockey and open-skill sports was not significant. However, DTC in closed-skill sports were significantly higher than in ice hockey and open-skill sport athletes, respectively. Since ST performance was better in ice hockey and other open-skill sport athletes than in closed-skill sport athletes, this is even more striking. Therefore, the data seems to verify the second hypothesis. These results make it plausible, that the ability to deal with this DT situation has relevance for ice hockey and open-skill sport performance in general. These findings are in line with the work of Schaefer and Scornaienchi (2020). They compared the performance of expert and novice table tennis players in a DT paradigm entailing returning balls from a ball machine and concurrently completing a working memory task (3-back task). The researchers found that in experts, performance reduction under DT conditions was less pronounced than in novices.

The fourth aim of the study was the comparison of DTC between teams regarding the influence of age on DTC. Due the results of Moreira et al. (2021) and the assumption that older athletes should have had greater exposure to DT scenarios, we expected the women's first team to show less DTC than the women's U18 and the men's U20 to show less DTC than the men's U18. The results showed no significant differences between teams; hence the fourth hypothesis cannot be confirmed. This begs the question if greater ability to handle DT is a valid marker for superior performance in ice hockey. One possible explanation for this might be that exposure to general ice hockey training develops DT ability to a certain level, that is reached with the U18 age category or prior. Specific cognitive-motor DT training might still be able to develop this ability further. Another possibility might be that a better ability to handle DT scenarios is a selection criterion for higher performance in ice hockey that is not causally linked to DT exposure. In this case, it could be an interesting tool for early talent identification. This result is, however, limited by the fact that no direct measure of exposure to DT scenarios, like training age, was taken.

The last aim of the study was to assess the relationship between DT performance and cognitive functions to potentially identify underlying resources. Based on the resource account of Wickens (2008) as well as the studies of Casella et al. (2022), Fleddermann et al. (2019) and Moreira et al. (2021), we expected that DTC performance would rely on cognitive performance. However, no significant regression model was found that was able to predict DTC based on the cognitive performances in the ZVT, d2-R, CBT forward and backward, 2CRT and SSRT. Accordingly, the fifth hypothesis must be discarded. These results conflict with the suggestion of Moreira et al. (2021), that "individuals with high working memory capacity could optimize attentional resources for solving cognitive task while performing the motor task" and the empirical work of Fleddermann et al. (2019), who found increased performance in the processing speed and sustained attention through DT training. The authors suggested processing speed (assessed through ZVT) and sustained attention (assessed through d2-R) as an underlying resource. However, they also found no effect on memory span and letter readout. Laurin and Finez (2020) examined the interaction of working memory capacity and different cognitive tasks paired with juggling in soccer. The tasks varied in cognitive load, to test if higher working memory capacity would allow better DT performance with secondary tasks of greater difficulty. Strikingly, they found that higher working memory capacity did not appear to be beneficial but detrimental to performance under DT situations of higher complexity. Casella et al. (2022) also found improvements in cognitive performance through cognitive-motor training, but in more complex tests, the Tower of London and WISC-IV cancellation test. These tests assess more complex constructs, like planning abilities and visual search abilities, and not simply cognitive functions. Kalén et al. (2021) differentiate the cognitive constructs (1) basic cognitive functions, (2) higher cognitive functions and (3) cognitive decision-making skills and find that the latter were better at differentiating between higher-and lower skilled athletes. The authors state that "whether the advantage of specific measures for discriminating expertise levels reflects a higher level of sensitivity, a better fit of the functions and skills needed for the task, or a reflection of the combination of selection and training processes is unclear." Scharfen and Memmert (2019) also found greater differences for cognitive skills in comparison to executive functions in elite athlete. This suggests that cognitive performance in sports, and possibly DT performance, are too complex and specific for basic or higher cognitive functions to explain great variance.

An alternative explanation for the differences in DTC might be the automatization of the employed tasks. Besides an increased capacity or resource, higher efficiency through greater degree of automatization might be an alternative adaptation to dual−/multi-tasking demands. This account assumes that processing evolves to a task-specific processing pipeline, decreasing the need for central resources (Wollesen et al., 2022). Langhanns and Müller (2018) discuss evidence for two motor regimes for repetitive movements, an automatic and a cognitively controlled regime. When a secondary cognitive task is performed simultaneously, cognitive control seems to be negatively affected, hence less automaticity could lead to greater DTC. On the one hand, this might explain the superiority of ice hockey and other open-skill sports in comparison to closed-skill sports, since the latter does not involve running, which has great similarities to the tapping task. On the other hand, there might be different levels of tapping and speed-reading automaticity within the sample of ice hockey players that could have affected the vulnerability to DTC.

This study is a valuable addition to the DT literature as it encompasses a great sample of elite athletes across multiple sports. The unique DT paradigm has enough specificity to discriminate between open-skill and closed-skill sports, but still allows assessment of a diverse spectrum of open-skill sports, that entail cyclical speed of the lower body and a concurrent visuo-verbal information processing. A limitation of this study is that only motor ST, DT and DTC were collected. This way, varying degrees of task prioritization between motor and cognitive task could not be registered. Additionally, the degree of specificity chosen to enable comparison across multiple open-skill sports, might have compromised the ability to discriminate differing ice hockey expertise levels. Lastly, athletes' psychological state or external factors, e.g., time of testing, might be factors of influence that we were not able to control.

5 Conclusion

This study established the efficacy of a novel DT paradigm entailing cyclical speed of the lower body and a concurrent visuo-verbal speed-reading task in inducing DTC in a diverse array of elite athletes. DTC and ST seem to be sufficiently independent for relevancy of testing DT. The performance in this DT paradigm seems to be able to distinguish between open-skill and closed-skill sport. No differences between national teams/age groups were found. There was no relationship between DT performance and cognitive functions. From a talent identification standpoint, assessing the ability of athletes to deal with cognitive-motor interference might be a valuable addition to a performance diagnostics battery in open-skill sports. From a development perspective, athletes that display good performance in conventional speed tests like sprinting, change of direction or jumping, but still seem to lack speed in game, might benefit from testing DT ability to tap into performance reserves.

Future research should investigate DT ability of athletes over a broader age range, including cognitive ST-, DT-performance and DTC. Furthermore, specific cognitive-motor DT training might be able to develop DT ability further and should be the focus of further scientific investigations. More specific DT paradigms should be employed to better assess the relationship between expertise levels and DT ability.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Ethikkommision Fachbereich 05, Goethe University Frankfurt. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

MB: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft. CK: Conceptualization, Investigation, Writing – original draft. LR: Data curation, Investigation, Writing – review & editing. KZ: Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This project was supported by the Bundesinstitut für Sportwissenschaft (German Federal Institute for Sport Sciences) in 2021 and 2022 (grant number ZMVI4-070703/21-22, "Kognitiv-motorisches Interferenztraining zur Verbesserung von spielbezogenen Schnelligkeitsleistungen"). This project was supported by the Bundesinstitut für Sportwissenschaft (German Federal Institute for Sport Sciences) in 2021-2025 (grant number 081901/21-25, "Individuelle Leistungsentwicklung im Spitzensport durch ganzheitliche und transdisziplinäre Prozessoptimierung").

Acknowledgments

We thank Björn Wieland, Marie-Therese Fledderman, Christina Willberg, Joshua Rettig, Kevin Happ, Andrea Roffler, Tim Schmitz, Merle Rosenkötter, Jan Münzberg, Till Müller, Liane Weber for support in the data collection. We would also like to thank all coaches and officials of the cooperating sport organisations and the athletes for their time and effort in this study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Amico, G., and Schaefer, S. (2022). Tennis expertise reduces costs in cognition but not in motor skills in a cognitive-motor dual-task condition. *Acta Psychol.* 223:103503. doi: 10.1016/j.actpsy.2022.103503

Antretter, E., Dunkel, D., and Haring, C. (2013). Wie zeitgemäß sind die in der deutschsprachigen Erwachsenenpsychiatrie verwendeten psychologischen Leistungstests? *Psychiatr. Prax.* 40, 120–129. doi: 10.1055/s-0032-1332988

Arce, T., and McMullen, K. (2021). The Corsi block-tapping test: evaluating methodological practices with an eye towards modern digital frameworks. *Comput. Hum. Behav Rep.* 4:100099. doi: 10.1016/j.chbr.2021.100099

Baldo, J. V., Shimamura, A. P., Delis, D. C., Kramer, J., and Kaplan, E. (2001). Verbal and design fluency in patients with frontal lobe lesions. *J. Int. Neuropsychol. Soc.* 7, 586–596. doi: 10.1017/s1355617701755063

Belghali, M., Chastan, N., Davenne, D., and Decker, L. M. (2017). Improving dual-task walking paradigms to detect prodromal Parkinson's and Alzheimer's diseases. *Front. Neurol.* 8:207. doi: 10.3389/fneur.2017.00207

Beurskens, R., Muehlbauer, T., Grabow, L., Kliegl, R., and Granacher, U. (2016a). Effects of backpack carriage on dual-task performance in children during standing and walking. *J. Mot. Behav.* 48, 500–508. doi: 10.1080/00222895.2016.1152137

Beurskens, R., Muehlbauer, T., and Granacher, U. (2015). Association of dual-task walking performance and leg muscle quality in healthy children. *BMC Pediatr.* 15:2. doi: 10.1186/s12887-015-0317-8

Beurskens, R., Steinberg, F., Antoniewicz, F., Wolff, W., and Granacher, U. (2016b). Neural correlates of dual-task walking: effects of cognitive versus motor interference in young adults. *Neural Plast.* 2016, 1–9. doi: 10.1155/2016/8032180

Bielmann, C., Castella, L., Andrey, P., Maystre, H., Hess, N., Fischer, K., et al. (2022). *Are Ice Hockey Players Becoming Faster and Stronger? A Nine-Year Trend Study of the Swiss U18 Men's Ice Hockey National Team*. [European College of Sport Science] Swiss Federal Institute of Sport, Magglingen. Available at: https://www.researchgate.net/profile/christian-bielmann-2/publication/364322604_are_ice_hockey_players_becoming_faster_and_stronger_a_nine-year_trend_study_of_the_swiss_u18_men's_ice_hockey_national_team/links/63480b52ff870c55ce215edc/are-ice-hockey-players-becoming-faster-and-stronger-a-nine-year-trend-study-of-the-swiss-u18-mens-ice-hockey-national-team.pdf (Accessed June 30, 2024).

Bond, C. W., Bennett, T. W., and Noonan, B. C. (2018). Evaluation of skating top speed, acceleration, and multiple repeated sprint speed ice hockey performance tests. *J. Strength Cond. Res.* 32, 2273–2283. doi: 10.1519/JSC.0000000000002644

Brickenkamp, R., Schmidt-Atzert, D., and Liepmann, D. (2010). d2-R–Aufmerksamkeits-und Konzentrationstest. Göttingen: Hogrefe Verlag.

Broadbent (1958). Perception and Communication. Oxford: Bergamo Press.

Broadbent, D. P., Causer, J., Williams, A. M., and Ford, P. R. (2014). Perceptual-cognitive skill training and its transfer to expert performance in the field: future research directions. *Eur. J. Sport Sci.* 15, 322–331. doi: 10.1080/17461391.2014.957727

Brown, L. §., and Ferrigno, V. (Eds.) (2015). Training for Speed, Agility, and Quickness. *3rd* Edn. Champaign: Human Kinetics.

Burr, J. F., Jamnik, R. K., Baker, J., Macpherson, A., Gledhill, N., and McGuire, E. J. (2008). Relationship of physical fitness test results and hockey playing potential in elite-level ice hockey players. *J. Strength Cond. Res.* 22, 1535–1543. doi: 10.1519/JSC.0b013e318181ac20

Casella, A., Ventura, E., and Di Russo, F. (2022). The influence of a specific cognitive-motor training protocol on planning abilities and visual search in young soccer players. *Brain Sci.* 12:1624. doi: 10.3390/brainsci12121624

Chaabouni, S., Methnani, R., Al Hadabi, B., Al Busafi, M., Al Kitani, M., Al Jadidi, K., et al. (2022). A simple field tapping test for evaluating frequency qualities of the lower limb neuromuscular system in soccer players: a validity and reliability study. *Int. J. Environ. Res. Public Health* 19:3792. doi: 10.3390/ijerph19073792

Chaddock, L., Neider, M. B., Voss, M. W., Gaspar, J. G., and Kramer, A. F. (2011). Do athletes excel at everyday tasks? *Med. Sci. Sports Exerc.* 43, 1920–1926. doi: 10.1249/MSS.0b013e318218ca74

Delis, D. C., Kaplan, E., and Kramer, J. H. (2001). Delis-Kaplan executive function System (D-KEFS) examiner's manual. United States: The Psychological Corporation.

Ericsson, K. A. (2003). Expert Performance in Sports: Advances in Research on Sport Expertise. Champaign: Human Kinetics.

Fait, P. E., McFadyen, B. J., Zabjek, K., Reed, N., Taha, T., and Keightley, M. (2011). Increasing task complexity and ice hockey skills of youth athletes. *Percept. Mot. Skills* 112, 29–43. doi: 10.2466/05.10.23.25.PMS.112.1.29-43

Farrell Pagulayan, K., Busch, R. M., Medina, K. L., Bartok, J. A., and Krikorian, R. (2006). Developmental normative data for the Corsi block-tapping task. *J. Clin. Exp. Neuropsychol.* 28, 1043–1052. doi: 10.1080/13803390500350977

Faubert, J., and Sidebottom, L. (2012). Perceptual-cognitive training of athletes. *J. Clin. Sport Psychol.* 6, 85–102. doi: 10.1123/jcsp.6.1.85

Fischer, R., and Plessow, F. (2015). Efficient multitasking: parallel versus serial processing of multiple tasks. *Front. Psychol.* 6:1366. doi: 10.3389/fpsyg.2015.01366

Fleddermann, M.-T., Heppe, H., and Zentgraf, K. (2019). Off-court generic perceptual-cognitive training in elite volleyball athletes: task-specific effects and levels of transfer. *Front. Psychol.* 10:1599. doi: 10.3389/fpsyg.2019.01599

Formenti, D., Trecroci, A., Duca, M., Cavaggioni, L., D'Angelo, F., Passi, A., et al. (2021). Differences in inhibitory control and motor fitness in children practicing open and closed skill sports. *Sci. Rep.* 11:4033. doi: 10.1038/s41598-021-82698-z

Ghasemzadeh, A., and Saadat, M. (2023). Cognitive mastery in sports: exploring cognitive Psychology's influence. *Health Nexus* 1, 41–49. doi: 10.61838/kman.hn.1.3.6

Göthe, K., Oberauer, K., and Kliegl, R. (2016). Eliminating dual-task costs by minimizing crosstalk between tasks: the role of modality and feature pairings. *Cognition* 150, 92–108. doi: 10.1016/j.cognition.2016.02.003

Gu, Q., Zou, L., Loprinzi, P. D., Quan, M., and Huang, T. (2019). Effects of open versus closed skill exercise on cognitive function: a systematic review. *Front. Psychol.* 10:1707. doi: 10.3389/fpsyg.2019.01707

Gutiérrez-Davila, M., Rojas, F. J., Gutiérrez-Cruz, C., and Navarro, E. (2017). Effect of dual-attention task on attack and defensive actions in fencing. *Eur. J. Sport Sci.* 17, 1004–1012. doi: 10.1080/17461391.2017.1332100

Hazeltine, E., Ruthruff, E., and Remington, R. W. (2006). The role of input and output modality pairings in dual-task performance: evidence for content-dependent central interference. *Cogn. Psychol.* 52, 291–345. doi: 10.1016/j.cogpsych.2005.11.001

Heilmann, F., Weinberg, H., and Wollny, R. (2022). The impact of practicing open-vs. closed-skill sports on executive functions - a meta-analytic and systematic review with a focus on characteristics of sports. *Brain Sci.* 12:1071. doi: 10.3390/brainsci12081071

Helm, F., Reiser, M., and Munzert, J. (2016). Domain-specific and unspecific reaction times in experienced team handball goalkeepers and novices. *Front. Psychol.* 7:882. doi: 10.3389/fpsyg.2016.00882

Heppe, H., and Zentgraf, K. (2019). Team handball experts outperform recreational athletes in hand and foot response inhibition: a behavioral study. *Front. Psychol.* 10:971. doi: 10.3389/fpsyg.2019.00971

Ishak, A. W. (2017). Communication in sports teams: a review. *Commun. Res. Trends* 36, 4–38. doi: 10.1108/978-1-80043-500-120211032

James, C. (2023). How Do Ice Hockey Players in Different Divisions Compare on Executive Functions? A Comparative Study of Athletes. [Master's Thesis, Umeå University].

Janelle, C. M., and Hillman, C. H. (2003). Expert Performance in Sport: Current Perspectives and Critical Issues. Champaign: Human Kinetics.

Kahneman, D. (1973). Attention and effort. *Am. J. Psychol.* 88:339. doi: 10.2307/1421603

Kalén, A., Bisagno, E., Musculus, L., Raab, M., Pérez-Ferreirós, A., Williams, A. M., et al. (2021). The role of domain-specific and domain-general cognitive functions and skills in sports performance: a meta-analysis. *Psychol. Bull.* 147, 1290–1308. doi: 10.1037/bul0000355

Koch, P., and Krenn, B. (2021). Executive functions in elite athletes – comparing open-skill and closed-skill sports and considering the role of athletes' past involvement in both sport categories. *Psychol. Sport Exerc.* 55:101925. doi: 10.1016/j.psychsport.2021.101925

Koch, I., Poljac, E., Müller, H., and Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking - an integrative review of dual-task and task-switching research. *Psychol. Bull.* 144, 557–583. doi: 10.1037/bul0000144

Krenn, B., Finkenzeller, T., Würth, S., and Amesberger, G. (2018). Sport type determines differences in executive functions in elite athletes. *Psychol. Sport Exerc.* 38, 72–79. doi: 10.1016/j.psychsport.2018.06.002

Lachter, J., Forster, K. I., and Ruthruff, E. (2004). Forty-five years after Broadbent (1958): still no identification without attention. *Psychol. Rev.* 111, 880–913. doi: 10.1037/0033-295X.111.4.880

Langhanns, C., and Müller, H. (2018). Empirical support for 'hastening-through-re-automatization' by contrasting two motor-cognitive dual tasks. *Front. Psychol.* 9:714. doi: 10.3389/fpsyg.2018.00714

Laurin, R., and Finez, L. (2020). Working memory capacity does not always promote dual-task motor performance: the case of juggling in soccer. *Scand. J. Psychol.* 61, 168–176. doi: 10.1111/sjop.12589

LeCouteur, A., and Feo, R. (2011). Real-time communication during play: analysis of team-mates' talk and interaction. *Psychol. Sport Exerc.* 12, 124–134. doi: 10.1016/j.psychsport.2010.07.003

Lundgren, T., Högman, L., Näslund, M., and Parling, T. (2016). Preliminary investigation of executive functions in elite ice hockey players. *J. Clin. Sport Psychol.* 10, 324–335. doi: 10.1123/jcsp.2015-0030

Mann, D. T., Williams, A. M., Ward, P., and Janelle, C. M. (2007). Perceptual-cognitive expertise in sport: a meta-analysis. *J. Sport Exerc. Psychol.* 29, 457–478. doi: 10.1123/jsep.29.4.457

Moratal, C., Lupiáñez, J., Ballester, R., and Huertas, F. (2020). Deliberate soccer practice modulates attentional functioning in children. *Front. Psychol.* 11:761. doi: 10.3389/fpsyg.2020.00761

Moreira, P. E. D., Dieguez, G. T., de Oliveira, B., da Glória Teles, S., and Praça, G. M. (2021). The acute and chronic effects of dual-task on the motor and cognitive performances in athletes: a systematic review. *Int. J. Environ. Res. Public Health* 18:1732. doi: 10.3390/ijerph18041732

Navabinejad, S., and Rostami, M. (2023). Mind and body in sync: the fascinating field of psychophysiology in sports. *Health Nexus* 1, 38–40. doi: 10.61838/kman.hn.1.3.5

Navon, D. (1984). Resources—a theoretical soup stone? *Psychol. Rev.* 91, 216–234. doi: 10.1037/0033-295X.91.2.216

Novák, D., Lipinska, P., Roczniok, R., Spieszny, M., and Stastny, P. (2019). Off-ice agility provide motor transfer to on-ice skating performance and agility in adolescent ice hockey players. *J. Sports Sci. Med.* 18, 680–694.

Oswald, W. D. (2016). ZVT-Zahlen-Verbindungs-Test. (3, Überarbeitete und Neu Normierte Auflage). Göttingen: Hogrefe Verlag.

Oswald, W., and Roth, E. (1987). Der Zahlen-Verbindungs-Test (ZVT), vol. *2*. Hofgrefe Verlag, Göttingen: Überarbeitete und Erweiterte Auflage.

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychol. Bull.* 116, 220–244. doi: 10.1037/0033-2909.116.2.220

Pashler, H. (1998). The Psychology of Attention. Cambridge: MIT Press.

Plummer, P., Zukowski, L. A., Giuliani, C., Hall, A. M., and Zurakowski, D. (2015). Effects of physical exercise interventions on gait-related dual-task interference in older adults: a systematic review and meta-analysis. *Gerontology* 62, 94–117. doi: 10.1159/000371577

Qiu, F., Pi, Y., Liu, K., Li, X., Zhang, J., and Wu, Y. (2018). Influence of sports expertise level on attention in multiple object tracking. *PeerJ* 6:e5732. doi: 10.7717/peerj.5732

Roczniok, R., Stanula, A., Maszczyk, A., Mostowik, A., Kowalczyk, M., Fidos-Czuba, O., et al. (2016). Physiological, physical and on-ice performance criteria for selection of elite ice hockey teams. *Biol. Sport* 33, 43–48. doi: 10.5604/20831862.1180175

Rost, D. H., and Hanses, P. (1993). Zur Brauchbarkeit des Zahlen-Verbindungs-Tests (ZVT) bei Kindern der 3. Jahrgangsstufe-psychometrische Überprüfung und Neustandardisierung. *Diagnostica* 39, 80–95.

Schaefer, S., and Scornaienchi, D. (2020). Table tennis experts outperform novices in a demanding cognitive-motor dual-task situation. *J. Mot. Behav.* 52, 204–213. doi: 10.1080/00222895.2019.1602506

Scharfen, H., and Memmert, D. (2019). Measurement of cognitive functions in experts and elite athletes: a meta-analytic review. *Appl. Cogn. Psychol.* 33, 843–860. doi: 10.1002/acp.3526

Schellig, D. (2011). Corsi-Block-Tapping-Test: Wiener Testsystem (Schuhfried, Mödlingen: Vienna Test System).

Solomito, M. J., Kostyun, R. O., Wu, Y. H., Mueske, N. M., Wren, T. A. L., Chou, L. S., et al. (2018). Motion analysis evaluation of adolescent athletes during dual-task walking following a concussion: a multicenter study. *Gait Posture* 64, 260–265. doi: 10.1016/j.gaitpost.2018.06.165

Stelzel, C., Schumacher, E. H., Schubert, T., and D'Esposito, M. (2006). The neural effect of stimulus-response modality compatibility on dual-task performance: an fMRI study. *Psychol. Res.* 70, 514–525. doi: 10.1007/s00426-005-0013-7

Stoet, G. (2010). Psytoolkit: a software package for programming psychological experiments using Linux. *Behav. Res. Methods* 42, 1096–1104. doi: 10.3758/BRM.42.4.1096

Stoet, G. (2017). Psy toolkit: a novel web-based method for running online questionnaires and reaction-time experiments. *Teach. Psychol.* 44, 24–31. doi: 10.1177/0098628316677643

Thomas, A. C. (2006). The impact of puck possession and location on ice hockey strategy. *J. Quant. Anal. Sports* 2:1007. doi: 10.2202/1559-0410.1007

Vaughan, R. S., and Laborde, S. (2021). Attention, working-memory control, working-memory capacity, and sport performance: the moderating role of athletic expertise. *Eur. J. Sport Sci.* 21, 240–249. doi: 10.1080/17461391.2020.1739143

Verbruggen, F., and Logan, G. D. (2008). Response inhibition in the stop-signal paradigm. *Trends Cogn. Sci.* 12, 418–424. doi: 10.1016/j.tics.2008.07.005

Verburgh, L., Scherder, E. J. A., van Lange, P. A., and Oosterlaan, J. (2014). Executive functioning in highly talented soccer players. *PLoS One* 9:e91254. doi: 10.1371/journal.pone.0091254

Vestberg, T., Gustafson, R., Maurex, L., Ingvar, M., and Petrovic, P. (2012). Executive functions predict the success of top-soccer players. *PLoS One* 7:e34731. doi: 10.1371/journal.pone.0034731

Vigh-Larsen, J. F., Beck, J. H., Daasbjerg, A., Knudsen, C. B., Kvorning, T., Overgaard, K., et al. (2019). Fitness characteristics of elite and subelite male ice hockey players: a cross-sectional study. *J. Strength Cond. Res.* 33, 2352–2360. doi: 10.1519/JSC.0000000000003285

Voss, M. W., Kramer, A. F., Basak, C., Prakash, R. S., and Roberts, B. (2010). Are expert athletes 'expert' in the cognitive laboratory? A meta-analytic review of cognition and sport expertise. *Appl. Cogn. Psychol.* 24, 812–826. doi: 10.1002/acp.1588

Wang, C.-H., Chang, C.-C., Liang, Y.-M., Shih, C.-M., Chiu, W.-S., Tseng, P., et al. (2013). Open vs. closed skill sports and the modulation of inhibitory control. *PLoS One* 8:e55773. doi: 10.1371/journal.pone.0055773

Westerlund, E., and Summanen, R. (2001). Let's Beat Them in Ice Hockey. Kuopio: Polar Elextro Oy.

Wickens, C. D. (2008). Multiple resources and mental workload. Human factors: the journal of the human factors and ergonomics. *Society* 50, 449–455. doi: 10.1518/001872008X288394

Wollesen, B., Müller, H., and Voelcker-Rehage, C. (2022). "Training based on multitasking–with a specific focus on motor-cognitive multitasking" in Handbook of Human Multitasking. Eds. Kiesel, A., Johannsen, L., Koch, I., and Müller, H (New York: Springer International Publishing), 347–397.

Yongtawee, A., Perk, J., Kim, Y., and Woo, M. (2021). Athletes have different dominant cognitive functions depending on type of sport. International journal of sport and exercise psychology (20). *Article* 20, 1–15. doi: 10.1080/1612197X.2021.1956570

Zhang, Y., Lu, Y., Wang, D., Zhou, C., and Xu, C. (2021). Relationship between individual alpha peak frequency and attentional performance in a multiple object tracking task among ice-hockey players. *PLoS One* 16:e0251443. doi: 10.1371/journal.pone.0251443

Zhu, H., Chen, A., Guo, W., Zhu, F., and Wang, B. (2020). Which type of exercise s more beneficial for cognitive function? A meta-analysis of the effects of open-skill exercise versus closed-skill exercise among children, adults, and elderly populations. *Appl. Sci.* 10:2737. doi: 10.3390/app10082737

frontiers | Frontiers in Psychology
TYPE Perspective
PUBLISHED 23 July 2024
DOI 10.3389/fpsyg.2024.1396873

Check for updates

OPEN ACCESS

EDITED BY
Sabine Schaefer,
Saarland University, Germany

REVIEWED BY
Florian Heilmann,
Martin Luther University of Halle-Wittenberg, Germany

*CORRESPONDENCE
Kim Huesmann
✉ kim.jana.huesmann@uol.de

RECEIVED 06 March 2024
ACCEPTED 10 July 2024
PUBLISHED 23 July 2024

CITATION
Huesmann K and Loffing F (2024) Perception-action coupling in anticipation research: a classification and its application to racket sports.
Front. Psychol. 15:1396873.
doi: 10.3389/fpsyg.2024.1396873

Perception-action coupling in anticipation research: a classification and its application to racket sports

Kim Huesmann[1]* and Florian Loffing[2]

[1]Department of Sport and Movement Science, Institute of Sport Science, Carl von Ossietzky University of Oldenburg, Oldenburg, Germany, [2]Section Performance Psychology, Institute of Psychology, German Sport University Cologne, Cologne, Germany

Anticipation is key to performance in many sports. By definition, anticipation as a perceptual-cognitive process is meant to inform action and help athletes reduce potential motor costs under spatiotemporal pressure. Anticipation research has repeatedly been criticized for neglecting action and raised the need for predominant testing under conditions of perception-action coupling (PAC). To the best of our knowledge, however, there is a lack of explicit criteria to characterize and define PAC conditions. This can lead to blurred terminology and may complicate interpretation and comparability of PAC conditions and results across studies. Here, we make a first proposal for a 7-level classification of PAC conditions with the defining dimensions of stimulus presentation and response mode. We hope this classification may constitute a helpful orientation for study planning and reporting in research on anticipation. Further, we illustrate the potential utilization of the PAC classification as a template for experimental protocol analysis in a review on anticipation in racket sports. Analysis of *N*=115 studies reported in *N*=91 articles confirms an underrepresentation of representative PAC conditions and reveals little change in PAC approaches over more than 40years of research in that domain. We discuss potential reasons for these findings, the benefits of adopting the proposed PAC classification and reiterate the call for more action in anticipation research.

KEYWORDS

ecological dynamics, embodied cognition, sensorimotor expertise, experimental design, representativeness, interaction, in-situ

1 Introduction

In many sporting contexts, athletes' performance depends on their skill to accurately foresee what is likely to happen in the next moment. In the sports science literature, that skill is traditionally referred to as anticipation (Abernethy, 1987; Loffing and Cañal-Bruland, 2017).[1] Specifically, anticipation is understood as the perceptual-cognitive process of predicting near future events (e.g.,

1 Occasionally, the term *visual anticipation* is used in the literature to indicate the prominent role of vision for anticipation (e.g., van der Kamp et al., 2008). We have deliberately omitted this specification as, in addition to visual information, auditory information, for example, presumably influences the anticipation process (e.g., Cañal-Bruland et al., 2018). Moreover, anticipation also relies on memory processes (e.g., knowledge of the opponent's action tendencies, general event probabilities; Loffing and Cañal-Bruland, 2017), so that we consider the neutral term anticipation more appropriate here.

an opposing tennis player's type and direction of serve) to enable optimal temporal and spatial alignment of one's own actions with these events (e.g., return of serve). Hence, anticipation is meant to guide an athlete's action. In view of this working definition of anticipation, scientists in the field frequently point out that research on anticipation needs representative testing environments that preserve the naturally occurring coupling between perception and action to draw conclusions on anticipation in the "real world" situation targeted in the investigation. More than 15 years back, for example, a focused debate emerged on the need for perception-action coupling (PAC) in sport-related anticipation research in a special issue of the *International Journal of Sport Psychology*. In their target article, van der Kamp et al. (2008) adopted an ecological approach and argued that in order to depict how athletes anticipate actions on field, perception and action need to be linked in a representative way. Similarly, Crognier and Féry (2007) conducted a review on anticipation research in tennis and criticized the broad use of experimental methods that separate the natural coupling of perception and action (also see Dicks et al., 2009). Until then, experimental approaches that evoke comparatively artificial PAC such as verbal or button responses to video stimuli in the lab were vastly employed 'by tradition' in sport-related anticipation research (Farrow and Abernethy, 2003). These approaches may come with certain benefits, such as better controllability of the testing environment, tasks, manipulation of independent and measurement of dependent variables as well as potential confounders which ultimately strengthen an experiment's internal validity. Additionally, feasibility of data collection in terms of cost, space and time efficiency might lead to a tendency to favorite comparatively artificial over more representative experimental designs. However, the experimental design of a study and its associated degree of representative[2] PAC influence the conclusions for research and practice scientists can infer toward real-world human behavior (Maselli et al., 2023; Raab et al., 2023). In this regard, the dominance of experimental approaches with little representative PAC in combination with an inconsistent description of PAC conditions potentially limits or even misleads our understanding of the sensorimotor processes underlying anticipation during sport-specific action and the expert advantage associated with it (for critical discussion, e.g., see Abernethy et al., 1993; van der Kamp et al., 2008; Dicks et al., 2009; Navia et al., 2018; Araújo et al., 2019).

Theories from ecological psychology propose a close bidirectional link between perception and action during movement execution. According to the ecological dynamics perspective (Araújo et al., 2006), there is continuous, ever evolving interaction between the environment, the actor and the task. This interaction produces affordances, that is opportunities for action, an actor can perceive and act upon. Experienced, in comparison to less experienced performers, are more attuned to relevant information and thereof evolving functional affordances which ultimately results in expertise-differences in anticipation and decision-making. However, the perspective argues that for real world (expertise in) anticipation and decision-making, actors need the possibility to perceive and act upon representative affordances (Travassos et al., 2017). The theories find support in sport scientific research investigating the influence of different PAC degrees on anticipation which indicate differences in anticipation and expertise effects depending on the experimental design and consequent PAC degrees used in studies (Farrow and Abernethy, 2003 in tennis; Ranganathan and Carlton, 2007 in baseball; Mann et al., 2010 in cricket; Huesmann et al., 2022 in handball). Beyond the ecological approach, other theoretical accounts also assume a close connection between perception and action, however, often with specific focus on particular aspects such as action observation, planning, initiation and execution (for an overview and systematization, e.g., see Gentsch et al., 2016).

Irrespective of the theoretical lens a study is specifically motivated by, the balanced discussion of results obtained from anticipation research and their associated potential implications (e.g., for practitioners) requires that researchers are able to describe and readers are able to understand, among others, the degree of PAC realized in a study. Two intertwined issues arise in this regard. First, to the best of our knowledge, there is a lack of explicit criteria to characterize and define PAC conditions. Second, the terms used for labeling the conditions under which participants are required to anticipate are frequently used inconsistently across studies. For example, Farrow and Abernethy (2003) asked participants to return a tennis serve in-situ and differentiated between two PAC conditions (uncoupled: verbal response; coupled: hit successful return stroke). Shim et al. (2005, Exp. 1), in turn, asked their participants to perform time-coupled on-court actions in response to tennis ground strokes presented either as point-light display, normal video (life-size screen projection) or a real opponent. The authors referred to all experimental conditions as perception-action coupled tasks without differentiating based on stimulus presentation. As another example, Ranganathan and Carlton (2007) used a virtual batting environment to study the effect of PAC by comparing batters' performance when giving an uncoupled verbal response as opposed to swinging a baseball bat against the virtual ball. The latter condition was considered coupled although realistic ball interception was not required. Collectively, without criticizing previous works' empirical merit, the former examples illustrate that different methodologies may underly the same label of PAC, whereas similar methodologies may underly different labels of PAC. Altogether, this potentially complicates interpretation and comparability of PAC conditions and results across studies.

Here we aim to take a first step toward a standardized PAC classification for anticipation research. Specifically, in the following section we propose a set of criteria to characterize different response modes in combination with different types of stimulus presentation for PAC classification. We then use this classification to exemplarily review the PAC conditions applied in research on anticipation in racket sports as a follow-up and extension to the overview provided by Crognier and Féry (2007) to illustrate the prevalence and temporal evolution of PAC approaches in that particular domain.

2 Perception-action coupling classification

Different levels of PAC have previously been defined based on the variation of participants' *response mode* (Farrow and Abernethy, 2003;

2 The term "representative" is defined by the ideas of Brunswik (1956), who stated that representative study design represents the typical environment and task constraints of the "real world task" targeted and intended to be generalized upon in the investigation (for an application of Brunswick's ideas to sports science see Pinder et al., 2011).

Farrow et al., 2005; Mann et al., 2010). We agree that this is the primary dimension along which PAC levels should be differentiated. However, we suggest that *stimulus presentation* should be added as a second dimension to allow more fine-grained differentiation of PAC levels (cf. Table 2 in Crognier and Féry, 2007, for a similar way to differentiate experimental protocols in anticipation research). This specifically applies to methodological approaches requiring a realistic (i.e., sport-specific), full-body movement either in response to videos or virtual reality as opposed to an in-situ condition against a real opponent. In the former situation, full coupling of a motor response to the stimulus display is not possible due to the missing opportunity for real interception, whereas in the latter case, interception is possible and participants may be specifically instructed to act accordingly (Farrow and Abernethy, 2003; Shim et al., 2005; Dicks et al., 2010). Further, consideration of stimulus presentation helps reduce the sole impact of response mode. We argue that requiring participants to act does not constitute a stronger case for PAC *per se* compared to when participants are not required to act but to, for example, make a verbal response. Specifically, this applies to situations when participants are confronted with still images as these do not provide a continuous flow of visual information participants' action might be coupled with (in contrast to, e.g., video or in-situ).

The classification we propose differentiates between seven levels of PAC (see Figure 1A; Table 1). The lowest (PAC 0) and highest level (PAC 6) indicate conditions of no and full representative PAC, respectively. For the first PAC-defining dimension of *response mode*, we suggest to differentiate between six modes as outlined in Table 1. Each of these modes is defined by five characteristics related to a response's temporal proximity to stimulus (far/near), its spatial alignment with stimulus (no/yes), temporal resolution (discrete/continuous), device used (artificial/realistic), and task-specificity of the action (non-specific/specific). Characteristics were chosen to enable unique assignment of response modes and to reflect a response's increasing representativeness (with regard to the constraints within the testing environment) relative to real-life demands from lowest (RM1) to highest mode (RM6). Examples for each of the six response modes are given in Table 1. For the second PAC-defining dimension of *stimulus presentation*, we suggest to differentiate between three types: still image, video/virtual reality (VR) and in-situ (see Travassos et al., 2013, for an identical differentiation of stimulus presentation). These types differ according to the flow of optical information related to an opponent's action (image: none; video/VR & in-situ: continuous) and the perceptual richness the to-be-anticipated action is embedded in (image to in-situ: very low to high).

We suggest to define PAC levels based on a combination of response mode and type of stimulus presentation. As still images do not provide a continuous flow of optical information toward which a response could be aligned irrespective of mode, we classified this as PAC 0. Also, responses of mode RM1 are classified as PAC 0 irrespective of stimulus presentation because this mode offers the lowest opportunity for representative action and its coupling with perception irrespective of the stimulus (see Table 1 for details on the characteristics of RM1). Specifically, requiring participants to respond, e.g., via paper-pen means they need to change attention from the

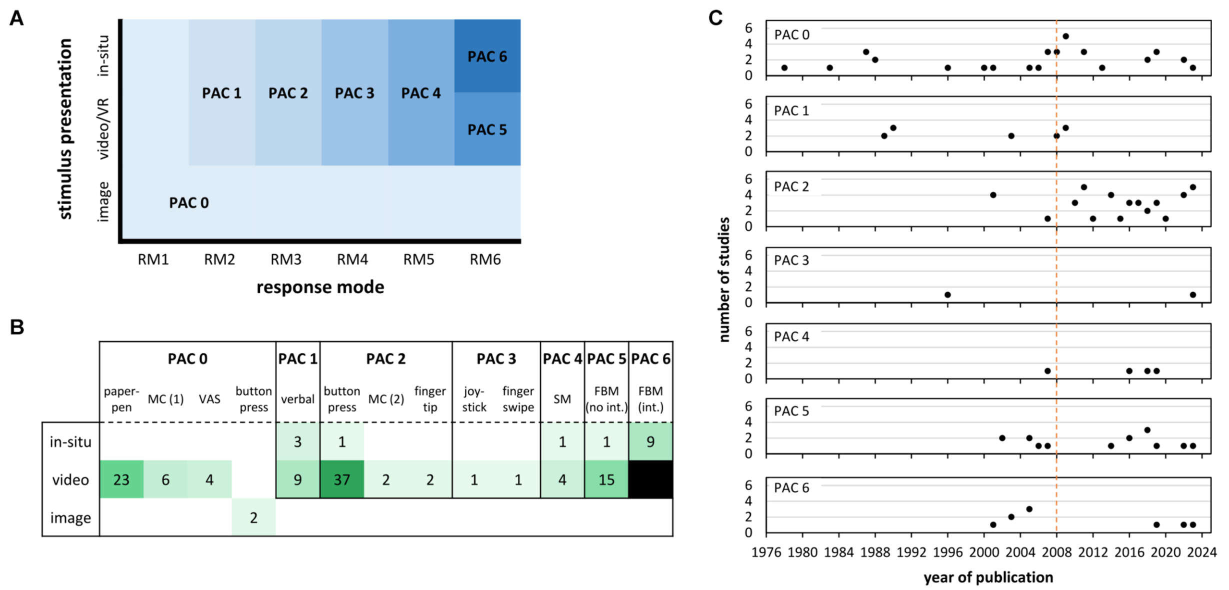


FIGURE 1
(A) Levels of perception-action coupling as defined by response modes RM1-6 and stimulus presentation (for details see Table 1). **(B)** Number of studies on anticipation in racket sports using a particular combination of response mode and stimulus presentation. Combinations are assigned to different levels of perception-action coupling (PAC) according to the criteria listed in Table 1. **(C)** Number of studies assigned to each PAC level by year of publication. The vertical dotted line indicates the year of a special issue on the coupling of perception and action in anticipation research with the much-regarded target article by van der Kamp et al. (2008). MC (1) = mouse click on a court representation (digital analog to a paper-pen response); MC (2) = mouse click (left/right) as directional response similar to button press; VAS = visual analog scale; SM = simple movement (e.g., foot toward left/right); FBM (no int.) = full-body movement (no interception); FBM (int.) = full-body movement with interception; PAC = perception-action coupling.

TABLE 1 Response mode and stimulus presentation as the two defining dimensions for the levels of perception-action coupling.

<table>
<tr><th></th><th colspan="6">Response mode</th><th colspan="3">Stimulus presentation</th><th></th></tr>
<tr><th>Code</th><th>(1) Temporal proximity to stimulus</th><th>(2) Spatial alignment with stimulus</th><th>(3) Temporal resolution</th><th>(4) Device</th><th>(5) Task-specificity</th><th>Example</th><th>Image</th><th>Video/VR</th><th>in-situ</th><th>Dependent variables, e.g.</th></tr>
<tr><td>RM1</td><td>Far</td><td>No</td><td>Discrete</td><td>Artificial</td><td>Non-specific</td><td>Paper-pen</td><td colspan="3">0</td><td>Accuracy/error, response time</td></tr>
<tr><td>RM2</td><td>Near*</td><td>No</td><td>Discrete</td><td>Artificial</td><td>Non-specific</td><td>Verbal</td><td rowspan="5">0</td><td colspan="2">1</td><td>Accuracy/error, response time</td></tr>
<tr><td>RM3</td><td>Near*</td><td>Yes</td><td>Discrete</td><td>Artificial</td><td>Non-specific</td><td>Button press (left, right)</td><td colspan="2">2</td><td>Accuracy/error, response time</td></tr>
<tr><td>RM4</td><td>Near</td><td>Yes</td><td>Continuous</td><td>Artificial</td><td>Non-specific</td><td>Joystick, mouse</td><td colspan="2">3</td><td>Same as above + movement time, movement dynamics (e.g., trajectory, corrections)</td></tr>
<tr><td>RM5</td><td>Near</td><td>Yes</td><td>Continuous</td><td>Realistic</td><td>Non-specific</td><td>Simple movement, e.g., step left/right</td><td colspan="2">4</td><td>Same as above</td></tr>
<tr><td>RM6</td><td>Near</td><td>Yes</td><td>Continuous</td><td>Realistic</td><td>Specific</td><td>Full-body movement, e.g., tennis return</td><td>5</td><td>6 (only if interception possible)</td><td>Same as above + temporal/spatial error relative to estimated position of projectile, sport-specific skill execution (e.g., timing, velocity, angle), temporal/spatial error, response outcome (e.g., serve return performance)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="3">PAC levels</td><td></td></tr>
</table>

* Temporal proximity for discrete responses contingent on task instructions, here assuming that participants are required to act timely as if in real competition. PAC, perception-action coupling; VR, virtual reality.

10.3389/fpsyg.2024.1396873

stimulus display (e.g., video, image) to the response display (e.g., sheet of paper), thus inducing a temporal gap between stimulus and response (i.e., far temporal proximity, see Table 1).

PAC levels 1–4 are defined solely based on response modes RM2 to RM5 and apply similarly to video/VR and in-situ within respective response modes (Table 1; Figure 1A). The guiding principle in differentiating these PAC levels is the gradual change along the five response mode characteristics. Specifically, at PAC 1 temporal proximity is near (e.g., verbal response can be given temporally connected to a critical stimulus event), but a response's spatial alignment with a stimulus is still not possible. The latter, however, is possible from PAC 2 onwards (e.g., left button press when a participant anticipates their opponent to hit a ball to their left). Further, at PAC 2, a response is still discrete and in PAC 3 responses are still given using an artificial device (e.g., via joystick) but they are continuous. Continuous responses allow for spatiotemporal corrections in the course of movements and thus may inform about changes of mind due to, e.g., updated beliefs regarding the most probable target for action (Savelsbergh et al., 2002; Cos et al., 2021). At PAC 4, the response device becomes realistic (i.e., the body) but the required response is still task-unspecific (e.g., simple movement such as step left/right). Overall, changes from far to near temporal proximity (PAC 0 ➔ PAC 1), possibility for spatial alignment with stimulus (PAC 1 ➔ PAC 2), from discrete to continuous responses (PAC 2 ➔ PAC 3) and from an artificial to a realistic device (PAC 3 ➔ PAC 4) create increasingly representative affordances, that is opportunities for action, which allow a step-by-step approximation to real-world task demands.

Finally, PAC 5 and 6 are characterized by task-specific responses (e.g., full-body movement such as tennis serve return). These two levels are further differentiated by *stimulus presentation*, with PAC 5 and PAC 6 applying to video/VR and in-situ conditions, respectively. Research realizing designs at PAC 5 and PAC 6 levels may inform about how anticipation guides action, the dynamics underlying cue utilization throughout the full course of an evolving opponent's action as well as the spatiotemporal adequacy of the full movement response. If a study is conducted in-situ and a task-specific full-body movement response without interception is required, we recommend to classify that condition as PAC 5. We suggest that a condition should be classified as PAC 6 only if participants are instructed to perform a realistic interception, for instance, of a ball moving toward them in the real-world performance environment (e.g., on-court in tennis). Consequently, the key difference between PAC 5 and PAC 6 is that PAC 6 might additionally allow for the assessment of response outcome (e.g., serve return performance; Table 1). This is not or only restrictedly (e.g., in VR) possible at PAC 5 and lower levels. Thus, in our view the assumption that anticipation is meant to guide an athlete's action is most extensively reflected in experimental protocols using PAC 6.

The PAC classification is meant to be used as orientation for the development of experimental protocols at the stage of study planning and the description of methods in, for instance, manuscripts to prepare a targeted discussion of results. Moreover, the classification may also be used as a template to analyze the experimental protocols reported in the literature. We next report the exemplar application of the PAC classification to cross-sectional research on anticipation in racket sports. By doing so, we aim to illustrate its use and reveal the prevalence and the temporal evolution of PAC approaches as a basis for a critical discussion of methodological developments and recommendations for future work.

3 Perception-action coupling approaches in racket sports

3.1 Methods

We followed the updated PRISMA guidelines (Page et al., 2021) and systematically searched the scientific literature using the search term [anticipat* AND (tennis OR "table tennis" OR badminton OR squash OR padel)] in three databases (PubMed [search field: all fields; $n = 167$], Web of Science [Core Collection; search field: topic; $n = 341$], Scopus [search field: title-abs-key; $n = 279$]; last updated search on February 13, 2024).[3] Original, peer-reviewed articles that reported a cross-sectional approach to investigate anticipation in racket sports were included if the full text was published in English or German. No restriction was made neither on the year of publication nor on the research discipline (e.g., sport science, psychology, neuroscience). Original studies reporting a training intervention were excluded just like any forms of reviews, meta-analyses, conference proceedings, project reports, book chapters or articles published in languages other than English or German. Moreover, studies were only included if sport-specific stimuli were presented (e.g., video opponent in a study on tennis serve return), and were excluded if a sport-*un*specific type of stimulus (e.g., runway of LEDs to investigate coincidence-anticipation; Ripoll and Latiri, 1997; Le Runigo et al., 2005) or only a ball machine was implemented (e.g., Alain et al., 1986) as both do not provide participants the opportunity to anticipate based on, for instance, advance kinematic (e.g., opponent's shoulder rotation) or contextual (e.g., opponent's on-court position) information. Also, studies were excluded if no measure of anticipation but only participants' visual search behavior was recorded on-court (e.g., Lin et al., 2021; Espino Palma et al., 2023). Finally, studies that were of purely observational nature were excluded because of the lack of at least partial control of the testing environment, although in general we consider such work highly valuable and informative with regard to describing anticipatory behavior in real racket-sport competition (e.g., Howarth et al., 1984; Triolet et al., 2013; Mecheri et al., 2019; Benguigui et al., 2024). The search protocol as well as an overview of the included studies, publication years, sports and experimental methods can be found in the Supplementary material. The focus of descriptive analysis using Microsoft Excel was on identifying the type of stimulus presentation and response mode as basis for determining the PAC level realized in the included studies.

3 Note that our review was not aimed at providing a full systematic review in the sense of an (almost) exhaustive coverage of the literature but rather to showcase the application of the PAC classification. Therefore, we kept the PRISMA route of identification of studies via other methods rather short and consequently cannot rule out that we have missed some reports, especially from earlier years, that are often not listed in databases (Supplementary Figure S1).

3.2 Results

A total of $N = 91$ articles published between 1978 and 2023 were identified eligible for inclusion (see Supplementary Figure S1 for a PRISMA flowchart). Most articles reported studies in tennis ($n = 60$), followed by badminton ($n = 18$), table tennis ($n = 10$) and squash ($n = 3$; none in padel). Overall, the articles reported a total of $N = 115$ studies (due to several multi-study reports) that were considered for a methodological analysis of PAC approaches (see Supplementary Table S1 for an overview of individual studies' classifications).

Accordingly, as is illustrated in Figure 1B, in most studies, participants viewed videos and responded via button press, a combination that belongs to PAC 2 according to our classification (see Table 1). The second most employed combination again was to show videos and ask for paper-pen responses (belonging to PAC 0), followed by full-body movements in response to videos (belonging to PAC 5), verbal responses to videos (belonging to PAC 1) and full-body movements with in-situ interception (belonging to PAC 6). When the different response mode and stimulus presentation combinations were considered overall and assigned to PAC levels, PAC 2 was most often realized, followed by PAC 0, 5, 1, 6, and 3 (Figure 1B).

A differentiated view on the number of studies conducted per PAC level by the year of publication is given in Figure 1C. Accordingly, research realizing the lowest level of PAC has the longest tradition and this approach is used regularly until today (PAC 0; top row in Figure 1C). Research realizing a PAC 2 (e.g., button press in response to video), in turn, has gained popularity from 2010 onwards. Requiring participants to perform full-body movements in response to video (PAC 5) or in-situ with interception (PAC 6) was introduced in the early 2000s (e.g., Abernethy et al., 2001). However, these methodological approaches did not become the dominant ones from then on, especially not in comparison to PAC 2 (Figure 1C).

4 Discussion

Different experimental designs all carry a particular degree of PAC. Motivated by theories that assume a close link between perception and action, such as the ecological dynamics perspective, researchers have repeatedly criticized the dominant separation of perception and action in studies on anticipation (Abernethy et al., 1993; Araújo et al., 2006, 2019; van der Kamp et al., 2008; Travassos et al., 2013). Consequently, there has been unequivocal call for more sport-specific action and the preservation of representative PAC to further our understanding of expert athletes' exceptional sensorimotor skills on the field (Prinz, 1997; van der Kamp et al., 2008; Gentsch et al., 2016; Maselli et al., 2023). Additionally, the current inconsistent use of terminology for the description of experimental methods caused by a lack of explicit criteria to characterize and define PAC conditions renders the proper interpretation of (the scope) of available studies difficult.

Here we made a first proposal for a criteria-based classification of PAC levels. The classification is hoped to help standardize methodological terminology, enable more targeted discussion of the results' scope and to stimulate the systematic, theory-driven comparison of the impact of different PAC levels particularly on anticipation, but potentially also on related perceptual-cognitive skills (e.g., decision-making, pattern recognition). Additionally, the classification is neutral in the sense that it is applicable to different sports and tasks (e.g., batting in cricket and baseball, goalkeeping in soccer and handball). As exemplified in our application to anticipation research in racket sports, the PAC classification may also serve as a template for the analysis of experimental protocols reported in the literature to identify methodological foci and trends as well as to reveal potential methodological gaps worth addressing and experimentally challenge theoretical predictions.

Our review revealed persistent and predominant use of rather artificial PAC approaches that especially require discrete button press or paper-pen responses (i.e., PAC 0-2; see Figures 1B,C). Thus, little seems to have changed over more than 40 years of anticipation research or since the much-noticed call for more action by van der Kamp et al. (2008; see the number of studies relative to the dotted orange line in Figure 1C). This, at least, pertains to the domain of racket sports and includes our own research on anticipation (e.g., Loffing et al., 2016; Huesmann and Loffing, 2019). However, we expect that the methodological landscape would not noticeably change when extending the view on other interceptive sports and tasks (for methodological advancements in research on decision-making, e.g., see Inns et al., 2023; Iskra et al., 2024).

Despite the evident calls for more action in anticipation research, why did higher PAC levels not become more common and maybe even standard over time? We suspect that the underlying reasons are manifold and intertwined. For example, experiments with low PAC are less resource demanding (e.g., button press in response to videos shown on a notebook monitor, results stored in easy to process logfiles) than experiments with high PAC (e.g., large labs or gyms and real opponents required, recording of participants' full-body movements, potentially in combination with motion capturing, as response mode, enhanced complexity in data processing and analyses due to multivariate datasets). Considering the research questions targetable with the different PAC levels, however, studies with lower PAC should not be discarded as less valuable in comparison to high PAC studies. Low-PAC studies might allow for a targeted and resource-efficient initial investigation of, for instance, the influence of selected information sources on skilled anticipation and this might then be followed up by studies using higher PAC to, e.g., test transfer to the field. Finally, as another potential reason, the evidence from studies that investigated the influence of different degrees of PAC on anticipation to date is indicative but not overly convincing (Mann et al., 2007; Travassos et al., 2013), for example, with regard to a more pronounced expertise advantage (Ranganathan and Carlton, 2007; Mann et al., 2010) or better anticipation performance at higher than lower PAC levels (Farrow and Abernethy, 2003; Huesmann et al., 2022). The classification presented here may help as orientation for future systematic theory-driven analysis of such PAC effects.

Still, we emphasize the call for strengthening the action component in anticipation research and to purposefully use it as an (in)dependent variable to, for instance, experimentally challenge the proposition that perception and action are linked bidirectionally (Araújo et al., 2006; Lepora and Pezzulo, 2015; Pizzera, 2016; Maselli et al., 2023; Voigt et al., 2023). Emerging technologies, such as for instance VR, can help researchers create experimental designs with high degrees of PAC while still allowing close control of the experimental setting, combining the advantages of high and low PAC levels. Further, there is continued interest in answering the questions on which kinematic and contextual sources are used for and how related information is computationally weighted and integrated in skilled anticipation (Loffing and Cañal-Bruland, 2017). The recent literature argues in favor of Bayesian computational models (Harris et al., 2022; Gredin et al., 2023), however, part of the evidence supporting this idea originates from approaches with rather low PAC using paper-pen (e.g., Harris et al., 2023) or button press (e.g., Loffing and Hagemann, 2014; Helm et al., 2020; for exceptions, see, e.g., Gredin et al., 2018; Murphy et al., 2018; Magnaguagno and Hossner, 2020). In our view, preserving the representative coupling between perception and action in this line of research (e.g., see Mann et al., 2013; Stone et al., 2014, for enabling realistic ball interception under controlled stimulus conditions) would make an even stronger case for 'Bayesian anticipation' and facilitate transfer of gained insights to the real setting where such computations are assumed to guide skilled performance.

Finally, the PAC classification proposed here (Figure 1; Table 1) is not without limitations. For example, we did not consider and further differentiate PAC levels depending on whether the temporal or spatial occlusion technique is part of an experimental protocol. This may be relevant, however, to keep in mind for, among others, in-situ studies that use liquid crystal googles to occlude participants' vision before ball flight. In situations like these, realistic task-specific interception will be difficult to achieve (e.g., Farrow and Abernethy, 2003). Also, PAC levels were defined without specifically differentiating between task instructions such as whether participants are required to respond as fast (or timely) and accurately as possible within a specific time frame or without time constraints. Instead, we implicitly assumed that the first type of instruction is used but if not, we suggest to report so and even consider downgrading a particular PAC level because the response's temporal proximity to a stimulus might not be given.

Overall, we would like to reiterate that the classification is meant as a first step toward a criteria-based systematization of PAC levels, but it is explicitly not meant as a tool to assess the quality of experimental methods used in studies. In that sense, we hope the classification will constitute a helpful orientation for researchers that facilitates both study planning and reporting, that it can serve as a tool for experimental protocol analysis as well as aid the transfer of knowledge to practice by classifying the methodological level of PAC at which evidence was obtained. Beyond the application to racket sports shown here as an example, the PAC classification can also be applied to other interceptive sports and tasks. Based on our historical record of the PAC levels realized in anticipation research in racket sports, we expect a similar pattern of findings in other domains of sport and would like to express the anticipatory wish of "A little more action, please!."

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

KH: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. FL: Conceptualization, Formal analysis, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Funding

The authors declare that financial support was received for the research, authorship, and/or publication of this article. The authors gratefully acknowledge the support of the Deutsche Forschungsgemeinschaft (DFG) and the Open Access Publication Fund of the Library and Information System (BIS; Carl von Ossietzky University Oldenburg, Germany) for covering article processing charges.

Acknowledgments

We thank Tobias Bormann and Anna Hoppe for their help during literature search and processing for the review on racket sports.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2024.1396873/full#supplementary-material

References

Abernethy, B. (1987). Anticipation in sport: a review. *Phys. Educ. Rev.* 10, 5–16.

Abernethy, B., Gill, D. P., Parks, S. L., and Packer, S. T. (2001). Expertise and the perception of kinematic and situational probability information. *Perception* 30, 233–252. doi: 10.1068/p2872

Abernethy, B., Thomas, K. T., and Thomas, J. T. (1993). "Strategies for improving understanding of motor expertise [or mistakes we have made and things we have learned!!]" in Cognitive issues in motor expertise. eds. J. L. Starkes and F. Allard (Amsterdam: Elsevier), 317–356.

Alain, C., Sarrazin, C., and Lacombe, D. (1986). "The use of subjective expected values in decision-making in sport" in Sport and elite performers. The 1984 Olympic scientific congress proceeding. ed. D. M. Landers (Champaign, IL: Human Kinetics), 1–6.

Araújo, D., Davids, K., and Hristovski, R. (2006). The ecological dynamics of decision making in sport. *Psychol. Sport Exerc.* 7, 653–676. doi: 10.1016/j.psychsport.2006.07.002

Araújo, D., Hristovski, R., Seifert, L., Carvalho, J., and Davids, K. (2019). Ecological cognition: expert decision-making behaviour in sport. *Int. Rev. Sport Exerc. Psychol.* 12, 1–25. doi: 10.1080/1750984x.2017.1349826

Benguigui, N., Rioult, F., Kauffmann, F., Miller-Dicks, M., and Murphy, C. P. (2024). Henri Cochet's theory of angles in tennis (1933) reveals a new facet of anticipation. *Sci. Rep.* 14:3364. doi: 10.1038/s41598-024-53136-7

Brunswik, E. (1956). Perception and the representative design of psychological experiments. Berkeley: University of California Press.

Cañal-Bruland, R., Müller, F., Lach, B., and Spence, C. (2018). Auditory contributions to visual anticipation in tennis. *Psychol. Sport Exerc.* 36, 100–103. doi: 10.1016/j.psychsport.2018.02.001

Cos, I., Pezzulo, G., and Cisek, P. (2021). Changes of mind after movement onset depend on the state of the motor system. *eNeuro* 8:ENEURO.0174-0121.2021. doi: 10.1523/eneuro.0174-21.2021

Crognier, L., and Féry, Y. A. (2007). 40 ans de recherches Sur l'anticipation en tennis: Une revue critique [40 years of research on anticipation in tennis: a critical review]. *Sci. Motricité* 62, 9–35. doi: 10.3917/sm.062.0009

Dicks, M., Button, C., and Davids, K. (2010). Examination of gaze behaviors under in situ and video simulation task constraints reveals differences in information pickup for perception and action. *Atten. Percept. Psychophys.* 72, 706–720. doi: 10.3758/app.72.3.706

Dicks, M., Davids, K., and Button, C. (2009). Representative task designs for the study of perception and action in sport. *Int. J. Sport Psychol.* 40, 506–524.

Espino Palma, C., Luis del Campo, V., and Muñoz Marín, D. (2023). Visual behaviours of expert padel athletes when playing on court: an in situ approach with a portable eye tracker. *Sensors* 23:1438. doi: 10.3390/s23031438

Farrow, D., and Abernethy, B. (2003). Do expertise and the degree of perception-action coupling affect natural anticipatory performance? *Perception* 32, 1127–1139. doi: 10.1068/p3323

Farrow, D., Abernethy, B., and Jackson, R. C. (2005). Probing expert anticipation with the temporal occlusion paradigm: experimental investigations of some methodological issues. *Mot. Control.* 9, 330–349. doi: 10.1123/mcj.9.3.330

Gentsch, A., Weber, A., Synofzik, M., Vosgerau, G., and Schütz-Bosbach, S. (2016). Towards a common framework of grounded action cognition: relating motor control, perception and cognition. *Cognition* 146, 81–89. doi: 10.1016/j.cognition.2015.09.010

Gredin, N. V., Bishop, D. T., Broadbent, D. P., Tucker, A., and Williams, A. M. (2018). Experts integrate explicit contextual priors and environmental information to improve anticipation efficiency. *J. Exp. Psychol. Appl.* 24, 509–520. doi: 10.1037/xap0000174

Gredin, N. V., Bishop, D. T., Williams, A. M., and Broadbent, D. P. (2023). The use of contextual priors and kinematic information during anticipation in sport: toward a Bayesian integration framework. *Int. Rev. Sport Exerc. Psychol.* 16, 286–310. doi: 10.1080/1750984X.2020.1855667

Harris, D. J., Arthur, T., Broadbent, D. P., Wilson, M. R., Vine, S. J., and Runswick, O. R. (2022). An active inference account of skilled anticipation in sport: using computational models to formalise theory and generate new hypotheses. *Sports Med.* 52, 2023–2038. doi: 10.1007/s40279-022-01689-w

Harris, D. J., North, J. S., and Runswick, O. R. (2023). A Bayesian computational model to investigate expert anticipation of a seemingly unpredictable ball bounce. *Psychol. Res.* 87, 553–567. doi: 10.1007/s00426-022-01687-7

Helm, F., Cañal-Bruland, R., Mann, D. L., Troje, N. F., and Munzert, J. (2020). Integrating situational probability and kinematic information when anticipating disguised movements. *Psychol. Sport Exerc.* 46:101607. doi: 10.1016/j.psychsport.2019.101607

Howarth, C., Walsh, W. D., Abernethy, B., and Snyder, C. W. (1984). A field examination of anticipation in squash: some preliminary data. *Aust. J. Sci. Med. Sport* 16, 6–10.

Huesmann, K., and Loffing, F. (2019). Contextual cue utilization in visual anticipation in tennis: on the role of an opponent's on-court position and skill. *Ger. J. Exerc. Sport Res.* 49, 304–312. doi: 10.1007/s12662-019-00597-y

Huesmann, K., Loffing, F., Büsch, D., Schorer, J., and Hagemann, N. (2022). Varying degrees of perception-action coupling and anticipation in handball goalkeeping. *J. Mot. Behav.* 54, 391–400. doi: 10.1080/00222895.2021.1984868

Inns, J., Petancevski, E. L., Novak, A. R., and Fransen, J. (2023). Decision-making assessments in youth team invasion game athletes: a systematic scoping review. *Int. J. Sports Sci. Coaching* 18, 2360–2381. doi: 10.1177/17479541231185779

Iskra, M., Voigt, L., and Raab, M. (2024). Accounting for dynamic cognition-action interaction in decision-making tasks in sports: A scoping review. *Sport, Exercise, and Performance Psychology*. Institute of Psychology, German Sport University.

Le Runigo, C., Benguigui, N., and Bardy, B. G. (2005). Perception-action coupling and expertise in interceptive actions. *Hum. Mov. Sci.* 24, 429–445. doi: 10.1016/j.humov.2005.06.008

Lepora, N. F., and Pezzulo, G. (2015). Embodied choice: how action influences perceptual decision making. *PLoS Comput. Biol.* 11:e1004110. doi: 10.1371/journal.pcbi.1004110

Lin, Y.-N., Pacheco, M., Lin, Y.-F., Huang, C.-T., and Lin, J.-H. (2021). The influence of expertise and experimental paradigms on the visual behavior of tennis athletes in returning a serve. *Kinesiology* 53, 271–279. doi: 10.26582/k.53.2.10

Loffing, F., and Cañal-Bruland, R. (2017). Anticipation in sport. *Curr. Opin. Psychol.* 16, 6–11. doi: 10.1016/j.copsyc.2017.03.008

Loffing, F., and Hagemann, N. (2014). On-court position influences skilled tennis players' anticipation of shot outcome. *J. Sport Exerc. Psychol.* 36, 14–26. doi: 10.1123/jsep.2013-0082

Loffing, F., Sölter, F., Hagemann, N., and Strauss, B. (2016). On-court position and handedness in visual anticipation of stroke direction in tennis. *Psychol. Sport Exerc.* 27, 195–204. doi: 10.1016/j.psychsport.2016.08.014

Magnaguagno, L., and Hossner, E.-J. (2020). The impact of self-generated and explicitly acquired contextual knowledge on anticipatory performance. *J. Sports Sci.* 38, 2108–2117. doi: 10.1080/02640414.2020.1774142

Mann, D. L., Abernethy, B., and Farrow, D. (2010). Action specificity increases anticipatory performance and the expert advantage in natural interceptive tasks. *Acta Psychol.* 135, 17–23. doi: 10.1016/j.actpsy.2010.04.006

Mann, D. L., Spratford, W., and Abernethy, B. (2013). The head tracks and gaze predicts: how the world's best batters hit a ball. *PLoS One* 8:e58289. doi: 10.1371/journal.pone.0058289

Mann, D. T. Y., Williams, A. M., Ward, P., and Janelle, C. M. (2007). Perceptual-cognitive expertise in sport: a meta-analysis. *J. Sport Exerc. Psychol.* 29, 457–478. doi: 10.1123/jsep.29.4.457

Maselli, A., Gordon, J., Eluchans, M., Lancia, G. L., Thiery, T., Moretti, R., et al. (2023). Beyond simple laboratory studies: developing sophisticated models to study rich behavior. *Phys Life Rev* 46, 220–244. doi: 10.1016/j.plrev.2023.07.006

Mecheri, S., Laffaye, G., Triolet, C., Leroy, D., Dicks, M., Choukou, M. A., et al. (2019). Relationship between split-step timing and leg stiffness in world-class tennis players when returning fast serves. *J. Sports Sci.* 37, 1962–1971. doi: 10.1080/02640414.2019.1609392

Murphy, C. P., Jackson, R. C., and Williams, A. M. (2018). The role of contextual information during skilled anticipation. *Q. J. Exp. Psychol.* 71, 2070–2087. doi: 10.1177/1747021817739201

Navia, J.-A., Avilés, C., López, S., and Ruiz, L.-M. (2018). A current approach to anticipation in sport / Un enfoque actual de la anticipación en el deporte. *Estud. Psicol.* 39, 1–19. doi: 10.1080/02109395.2017.1412705

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., et al. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 372:n71. doi: 10.1136/bmj.n71

Pinder, R. A., Davids, K., Renshaw, I., and Araujo, D. (2011). Representative learning design and functionality of research and practice in sport. *J. Sport Exerc. Psychol.* 33, 146–155. doi: 10.1123/jsep.33.1.146

Pizzera, A. (2016). "Chapter 13 - bridging the gap between perception and action: an overview" in Performance psychology. eds. M. Raab, B. Lobinger, S. Hoffmann, A. Pizzera and S. Laborde (San Diego: Academic Press), 207–221.

Prinz, W. (1997). Perception and action planning. *Eur. J. Cogn. Psychol.* 9, 129–154. doi: 10.1080/713752551

Raab, M., Voigt, L., Rothkopf, C., and Fiehler, K. (2023). Studying naturalistic actions requires research programs and not trade-off decisions in individual studies: comment on "beyond simple laboratory studies: developing sophisticated models to study rich behavior" by Maselli, Gordon, Eluchans, Lancia, Thiery, Moretti, Cisek, and Pezzulo. *Phys Life Rev* 47, 33–34. doi: 10.1016/j.plrev.2023.08.014

Ranganathan, R., and Carlton, L. G. (2007). Perception-action coupling and anticipatory performance in baseball batting. *J. Mot. Behav.* 39, 369–380. doi: 10.3200/JMBR.39.5.369-380

Ripoll, H., and Latiri, I. (1997). Effect of expertise on coincident-timing accuracy in a fast ball game. *J. Sports Sci.* 15, 573–580. doi: 10.1080/026404197367001

Savelsbergh, G. J. P., Williams, A. M., van der Kamp, J., and Ward, P. (2002). Visual search, anticipation and expertise in soccer goalkeepers. *J. Sports Sci.* 20, 279–287. doi: 10.1080/026404102317284826

Shim, J., Carlton, L. G., Chow, J. W., and Chae, W. S. (2005). The use of anticipatory visual cues by highly skilled tennis players. *J. Mot. Behav.* 37, 164–175. doi: 10.3200/JMBR.37.2.164-175

Stone, J. A., Panchuk, D., Davids, K., North, J. S., Fairweather, I., and Maynard, I. W. (2014). An integrated ball projection technology for the study of dynamic interceptive actions. *Behav. Res. Methods* 46, 984–991. doi: 10.3758/s13428-013-0429-8

Travassos, B., Araújo, D., Davids, K., O'Hara, K., Leitão, J., and Cortinhas, A. (2013). Expertise effects on decision-making in sport are constrained by requisite response behaviours – a meta-analysis. *Psychol. Sport Exerc.* 14, 211–219. doi: 10.1016/j.psychsport.2012.11.002

Travassos, B., Davids, K., Araújo, D., and Esteves, T. P. (2017). Performance analysis in team sports: advances from an ecological dynamics approach. *Int. J. Perform. Anal. Sport* 13, 83–95. doi: 10.1080/24748668.2013.11868633

Triolet, C., Benguigui, N., Le Runigo, C., and Williams, A. M. (2013). Quantifying the nature of anticipation in professional tennis. *J. Sports Sci.* 31, 820–830. doi: 10.1080/02640414.2012.759658

van der Kamp, J., Rivas, F., van Doorn, H., and Savelsbergh, G. (2008). Ventral and dorsal system contributions to visual anticipation in fast ball sports. *Int. J. Sport Psychol.* 39, 100–130.

Voigt, L., Friedrich, J., Grove, P., Heinrich, N., Ittlinger, S., Iskra, M., et al. (2023). Advancing judgment and decision-making research in sport psychology by using the body as an informant in embodied choices. *Asian J. Sport Exerc. Psychol.* 3, 47–56. doi: 10.1016/j.ajsep.2022.09.006