Research Topics

The cognitive era in sports performance: mental fatigue, cognitive training, and psychological ergogenic substances

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The cognitive era in sports performance: mental fatigue, cognitive training, and psychological ergogenic substances

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Editorial: The cognitive era in sports performance: mental fatigue, cognitive training, and psychological ergogenic substances

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Editorial on the Research Topic
The cognitive era in sports performance: mental fatigue, cognitive training, and psychological ergogenic substances

Unlocking athletic potential through cognitive science

The landscape of elite sports is undergoing a paradigm shift. While physical prowess remains foundational, the next frontier of athletic excellence lies in the mind. A growing body of research demonstrates that cognitive, perceptual, emotional, and motivational factors and interventions—and their underlying neurobiology—play a decisive role in human performance. This editorial synthesizes key findings from recent studies published in *Frontiers in Psychology*, highlighting how psychology and cognitive neuroscience are reshaping training, competition, and recovery in sports.

The role of psychological interventions

The influence of mental training on athletic performance might no longer be speculative. A randomized controlled trial on Chinese sprinters (Yu et al.) revealed that a 7-week mindfulness program significantly reduced competition anxiety, enhancing somatic and cognitive self-regulation. These findings align with broader evidence that psychological skills training—once considered supplementary—is now essential for peak performance. Nevertheless, despite these advances, performance breakdown under pressure remains a challenge. Interestingly, Thiessen et al. found no direct link between self-reported mental toughness and choking susceptibility, challenging conventional wisdom and underscoring the need for more nuanced models of performance breakdowns in high-stakes scenarios.

Perceptual-cognitive skills: the hidden edge in sports

Elite performance in fast-paced, open-skill sports (e.g., badminton, fencing) relies on rapid decision-making and spatial awareness. Wu K.-C. et al. demonstrated that working memory capacity distinguishes elite adolescent badminton players from their semi-elite counterparts. Similarly, expert sports officials (Wu Y. et al.) exhibit superior decision-making accuracy and visual efficiency, suggesting that perceptual-cognitive factors are relevant to both athletes and referees.

Spatial cognition has also been linked to sports performance. Feng et al. revealed that athletes in high-spatial-demand sports (e.g., gymnastics, tennis) outperform others in mental rotation tasks, with axial rotation experience mitigating traditional sex differences in spatial ability. These studies suggest that perceptual-cognitive tests and training should be included in the talent identification and training programs of both athletes and referees to improve sports performance.

Mental fatigue: the silent performance thief in elite sports

While physical fatigue is relatively well-managed in elite sports, mental fatigue (MF) remains an under-addressed performance thief. Bian et al. and de Lima-Junior et al. highlight their potential effects: national-level fencers report heightened MF during elimination rounds, while swimmers experience inflated perceptions of effort and impaired race performance—despite unchanged physiological metrics. These findings demand that coaches, psychologists, and other members of the performance team consider the psychological load sustained by their athletes inside and outside their sports environment to prevent mental fatigue. Training and cognitive strategies specifically targeting mental fatigue must also be further developed.

You et al. examined conscious movement control and inhibition, highlighting this shift, revealing that an athlete's tendency to monitor movements consciously—often seen in high-pressure scenarios—can either enhance or hinder performance depending on task demands and mental fatigue. While simple actions may not benefit from overthinking, complex or reactive skills (like stopping a movement mid-action) may rely on conscious control, particularly when cognitive resources are depleted. These findings underscore the importance of individualized training approaches, blending implicit learning with strategic focus cues and preparing athletes to perform under mental fatigue. As sports enter the cognitive era, optimizing the interplay between automaticity and conscious control will be key to unlocking peak performance.

Beyond open vs. closed skills: cognitive demands matter

Recent findings challenge the assumption that open-skill sports (e.g., football) inherently sharpen executive functions more than closed-skill sports (e.g., golf) is being challenged. Li et al. found that 16 weeks of golf training improved inhibitory control comparably to football, suggesting that cognitive demand, not just sport classification, drives neurocognitive benefits. It expands the horizon for using closed-skill disciplines in cognitive training.

Motivation and motor learning: the power of choice and reward

Quan et al. close the loop with a compelling insight: reward and autonomy (voluntary choice) independently boost motor skill acquisition. Though their effects fade in retention, their synergy during training could optimize skill refinement—a principle applicable from rehabilitation to elite coaching. Supporting this, a study on motivational imagery Habib et al. demonstrated its effectiveness: when tested on 20 female undergraduates, motivational imagery significantly increased intrinsic motivation and physical activity over 12 weeks compared to a general physical activity imagery intervention, reinforcing motivational imagery as a cognitive-behavioral strategy to enhance engagement in exercise.

Toward a cognitive revolution in sports science

Collectively, these studies signal a transformative era where cognitive abilities such as strength, speed, and endurance are recognized as critical to sports performance. However, these studies highlight the complex interaction between cognitive, perceptual, emotional, and motivational factors. Therefore, it is important to consider the whole athlete's psychology as well as the underlying neurobiology. Future research must further integrate psychology and neurobiology and fill gaps, e.g., longitudinal studies of cognitive skills development and individualized mental fatigue monitoring and management. One conclusion is becoming clear: the mind/brain is the next frontier of performance enhancement.

Cognitive training is just as important as physical training in sports. We suggest that future studies focus on mental coaching that combines brain science with athletic training to help athletes perform at their best, both mentally and physically.

Implications for practice

- Integrate mindfulness and cognitive training into regimens to reduce anxiety and sharpen decision-making.
- Monitor and mitigate mental fatigue with tailored recovery protocols.
- Prioritize sport-specific perceptual-cognitive drills to accelerate expertise.
- Leverage autonomy and reward structures to optimize motor learning.

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A comparison of perceptual-cognitive skills in expert and non-expert sports officials: a systematic review and meta-analysis

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Introduction: The purpose of this study is to systematically compare and assess the differences in perceptual-cognitive skills between expert and non-expert sports officials, and further explore the potential differences caused by different types of sports officials, in order to provide a more comprehensive understanding of the perceptual-cognitive skills of sports officials.

Methods: Relevant literature published before 31 December 2022 was searched in four English databases. Review Manager 5.4 and Stata 12.0 software were used for meta-analysis and bias test.

Results: Expert sports officials are significantly more accurate in their decision-making than non-expert sports officials, and exhibit a large amount of effect size (SMD = 1.09; 95%CI: 0.52, 1.66; $P < 0.05$). Expert sports officials had significantly fewer number of fixations than non-expert sports officials and showed a moderate amount of effect size (SMD = 0.71; 95%CI: 1.25, 0.17; $P < 0.05$). Expert sports officials' duration of fixation (SMD = 0.23; 95%CI: 0.25, 0.71; $P = 0.35$) were not significantly different from non-expert sports officials.

Discussion: It can be seen that there are differences in the Perceptual-cognitive skills of expert and non-expert sports officials. Decision-making accuracy can serve as an important indicator for distinguishing the perceptual-cognitive skills of expert and non-expert sports officials. Number of fixations can serve as important indicators to differentiate the perceptual-cognitive skills of monitors.

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1 Introduction

In the process of movement, the environment often contains a large amount of information. However, human capacity to process these information is limited, and active observer has to select the relevant signs from the large amount of information available in the environment (Moeinirad et al., 2020). This ability of an individual to identify and acquire environmental information and integrate it with existing knowledge in order to process information and execute appropriate responses in complex tasks is known as perceptual-cognitive skills (Marteniuk, 1976). Related research has demonstrated that the ability to acquire visual information and to select and execute appropriate movements is key to high-level performance and even plays a critical role in sports (Williams and Ericsson, 2005; Williams et al., 2011). Skilled experts have been found that to be superior on a variety of perceptual-cognitive tasks. Such as anticipation, the ability to predict the action of others based on early visual information (Abernethy and Russell, 1987); Decision-making, the ability to select the best option from a variety of alternatives (Helsen and Pauwels, 1993). Recall, the ability to recall previously seen situations (Allard et al., 1980). It has been shown that experts tend to be able to focus their attention on searching for relevant cues and making quick and accurate decisions in a game situation filled with a lot of information, while non-experts are less able to do so. Thus, it is these perceptual-cognitive skills that often serve as an important basis to distinguish experts from non-experts (Ward and Williams, 2003; Mann et al., 2007).

A large number of researchers have made it clear that with certain visual search behavior expert athletes can make proficient anticipation, alleviate the temporal constraints of the task and make fast and more accurate decisions than non-expert athletes (Helsen and Starkes, 1999). The investigation of gaze behavior seems to be an appropriate approach to better understand the visual attention and the perceptual-cognitive processes in information search (Mack, 2020). Williams and Ericsson (2005) argue that with certain visual search strategies, experts can achieve anticipation of extended movement cues, recognition of movement pattern, and the use of information. In sports situations, athletes need to pay attention to the most critical cues if they want to achieve superior performance. Therefore, more research has attempted to study the perceptual-cognitive skills of athletes in terms of selective attention and visual search abilities. The expert-novice research paradigm is currently the main research paradigm in the field of eye movements and provides an important basis for exploring experts high-level motor performance. Some researchers have shown that gaze behavior can be explicitly used as a process tracing measure for decision making. The decision making skills of expert athletes could also be directly traced to gaze behavior, thereby making the study of gaze behavior essential for all sports (Mann et al., 2009).

Indeed, numerous researchers have used eye tracking systems to test the gaze patterns of athletes as they attempt to anticipate or judge skilled performance in both laboratory and field settings (Mann et al., 2019). Researchers often focus on the location, sequence, number, and duration of fixations in athletes. The location and sequence of fixations are important enough to reflect the signs used in decision-making, and the number and duration of fixations reflect the need for information processing and the allocation of attention. There have also been some experimental studies that have measured the performance of athletes when using perceptual-cognitive skills for decision-making through reaction time and response accuracy (Williams et al., 1994; Guizani et al., 2006; Piras et al., 2014; Ottoboni et al., 2015). Reaction time refers to the objective length of time between the onset of a stimulus and the production of an apparent response, while response accuracy is the frequency of producing in which an appropriate response is made according to objective standards and task constraints. In general, expert athletes can demonstrate better accuracy over short period of time after a long period of training. They spend less time scanning for relevant environmental information, which keeps their attention focused on important place and lasts longer. Vickers and Adolphe (1997) used eye movement techniques to study the visual tracking of expert and non-expert volleyball players and found that expert players tracked the ball earlier and visually tracked the ball longer than non-experts. Panchuk and Vickers (2006) in their study of visual gaze characteristics of ice hockey goalies, found that ice hockey goalies' accurate spatial and temporal judgment of incoming pucks was dependent on the timing of visual orientation and visual tracking prior to the save. Great hockey goalies look at the incoming puck sooner, keep their eyes on the puck for longer before making a save, and rarely look at the attacking player's body. Thus, longer fixation times seem to imply more extraction of important information as well as more detailed information processing. The fundamental difference between experts and non-experts seems to be that experts are better able to extract and process information distributed throughout the body (Abernethy et al., 2008).

While abundant research has shown how athletes make decisions at a perceptual-cognitive level, relatively little research has focused on the decision-making performance and perceptual-cognitive skills of sports officials. Given the association among anticipation, gaze behavior, and decision-making accuracy in athletes, it is important to study these perceptual-cognitive processes in sports officials (Mann et al., 2007). Sports officials have played an essential and significant role in today's sports events since the emergence of modern athletics. They are appointed in most sporting competitions to ensure that the rules of the game are implemented (Bar-Eli et al., 2011). The sports officials are crucial in maintaining the fairness and impartiality of sporting events, and their activities directly affects the athletes' abilities. Indeed, perceptual-cognitive skills are just as important for sports officials as for athletes. Sports officials required to observe a large amount of information under strict time constrains, and use these information to make timely and accurate decision which are heavily scrutinized by athletes, coaches and spectators (Plessner and Haar, 2006). The main task of a sports official in a game is to accurately perceive complex situations, quickly process key cues, and consistently make correct and reasonable decisions (MacMahon et al., 2014). Perceptual-cognitive superiority in the sports domain can be assessed either in a sport-specific context representing the requirements of a competitive and realistic setting (domain-specific skills, such as decision-making performance) or by use of more generic tests with no direct link to the performance setting (domain-generic skills, such as local information processing; Spitz et al., 2018). Expert sports officials tend to perform better than non-experts on domain-specific tests, but have more complex results on domain-specific skills. The reason for the difference in the performance of expert and non-expert sports officials may be related to the anticipation of sports officials. Expert sports officials can rely on spatial or time anticipation to make predictions about the environment and determine behavior (Schrödter et al., 2023). Therefore, it is pivotal to examine how sports officials direct their vision to obtain information from the game, and subsequently make decisions at the perceptual-cognitive level, for a comprehensive assessment of their performance.

As previously noted, sports officials' decisions and predictions are affected by visual search behavior at the perceptual-cognitive level, enabling them to execute their activities with greater efficiency. Current academic research on sports officials' perceptual-cognitive skills, visual search behavior, and decision-making is considerably less prevalent than that of athletes. Although the total number of related studies is limited and their findings are inconclusive, certain scholars have experimentally demonstrated differences among sports officials in perceptual-cognitive skills and visual search behavior. Aghakhanpour et al. (2021) examined the decision-making and visual search patterns of fencing referees, revealing that expert referees demonstrated greater decision-making accuracy than novice referees. Furthermore, expert referees had fewer fixations and longer fixation duration compared to novice referees. Similar findings were discovered in Bard et al. (1980) research on gymnastics judges and Kostrna and Tenenbaum (2022) research on baseball umpires. However, studies by Hancock and Ste-Marie (2013) and Catteeuw et al. (2009) point out that there is no difference between expert and non-expert referees in visual search behavior. Ziv et al. (2020) conducted a review of sports officials' visual behavior in different sports. Their analysis of 12 studies showed that seven studies revealed variations in visual behavior among sports officials of different skill levels, while the remaining four studies found no differences. The authors suggested that sports officials display distinctive visual search patterns across various sport contexts and tasks. In fact, the decision-making demands of sports officials will also vary depending on the complexity of the task. To help explain the differences in sporting officials' performance demands, MacMahon classified officials by their respective movement, perceptual and competition interaction demands. This resulted in three specific groups of sports officials including, monitors (such as gymnastics judge), reactors (such as tennis line judge), and interactors (such as soccer referee; MacMahon et al., 2014). In these three types of sports officials, interactor have greater movement and fitness demands and are required to process multiple decision cues and interact with greater numbers of players. For example, interactors' decisions are often made under strict time and information constraints, require deep prior knowledge and efficiency in appraising and processing perceptual information, and involve a high degree of mental and physical fatigue (Kittel et al., 2021). Such complex demands may make the interactors inferior to the monitors and reactors in perceptual-cognitive performance. Although sports officials can be classified as interactors, monitors and reactors, further research is needed to clarify the specific differences in perceptual-cognitive skills between expert and non-expert sports officials.

Based on the above theories and background, the purpose of this study is to systematically compare and assess the differences in perceptual-cognitive skills between expert and non-expert sports officials, and further explore the potential differences caused by different types of sports officials, in order to provide a more comprehensive understanding of the perceptual-cognitive skills of sports officials. We applied meta-analysis to help us quantitatively evaluate specific differences in perceptual-cognitive skills between expert and non-expert sports officials. In addition, different types of sports officials face different task demands, which can lead to different criteria of decision-making and visual search strategies. Given that the type of sports official may be a potential factor affecting the perceptual-cognitive skills of experts and non-experts, we divided sports officials into interactors, reactors and monitors to further analyze and discuss according to MacMahon's classification.

2 Methods

2.1 Search strategies

The study protocol for this systematic review and meta-analysis was registered at PROSPERO with the registration number (CRD42023418594). To search as much relevant articles as possible, a systematic and comprehensive search was conducted in four English databases: Pubmed, Web of Science, EBSCO-SPORTDiscus, and EBSCO-MEDLINE. Specific search criteria were established following the PRISMA guidelines, the preferred report for systematic review and meta-analysis. Two independent researchers performed an initial screening of the titles and abstracts. Relevant articles published prior to 31st December 2022 was primarily searched. In each database, the keywords used when searching were as followed: (anticipation OR prediction OR decision-making OR expertise OR cue use OR information processing OR cognitive characteristics OR visual search OR visual attention OR visual fixation OR eye movement OR eye-tracking OR perceptual cognitive skills OR expert OR non-expert OR amateur OR novice OR elite) AND (referee OR judge OR judgment OR umpire OR official OR officiate). The detailed search process can be found in the Supplementary Table 1.

2.2 Inclusion and exclusion criteria

The study included the articles according to the following criteria: (1) Full-text articles. (2) Article published in English. (3) Articles must be based on an expert/non-expert paradigm and include both expert and non-expert groups. (4) Articles should report the sample size of the participants as well as the mean and standard deviation of the relevant metrics. In addition, the inclusion criteria of selected studies were based on the PICOS principle: P-participant, sports officials. I-intervention, experts with more expertise and experience. C-comparison, non-experts have less expertise and experience. O-outcome, results related to perceptual-cognitive skills include decision-making accuracy, number of fixation, and duration of fixation. S-study, study with expert/non-expert research paradigm.

Articles that does not meet the following criteria will also be excluded: (1) Means and standard errors for variables in the study are not reported. (2) Abstracts, research programme, news reports, dissertations, reviews and case reports from congress meetings or proceedings. (3) Literature for which the full text was not available or could not be downloaded.

The full text of studies that met the criteria was further reviewed by two independent researchers after an initial screening based on inclusion and exclusion criteria. If two researchers disagree on the assessment of the research literature reviewed, a third researcher is consulted and a decision made. A total of 16 eligible and relevant papers were finally included.

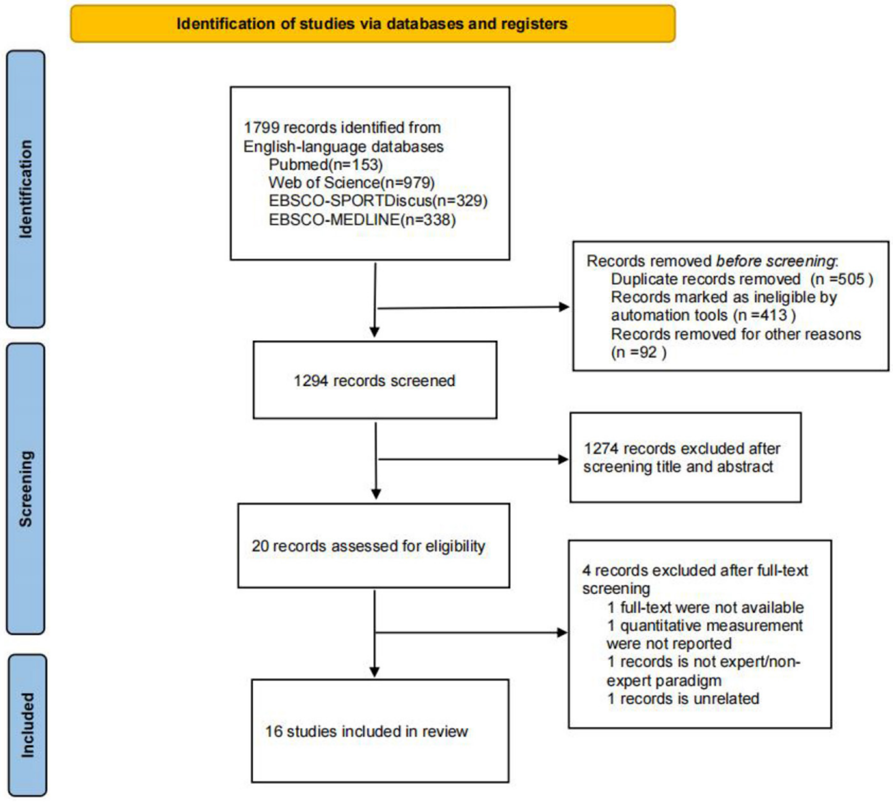

FIGURE 1
PRISMA flow diagram.

2.3 Outcome of assessment

This study selected decision-making accuracy, number of fixations, and duration of fixations as measurable indicators of perceptual-cognitive skills. The specific definition and measurement of these indicators are described below. The researchers of measured these indicators by recording participants' responses and visual characteristics when they watch the video clips identified by experts. Decision-making accuracy represents the frequency of producing in which an appropriate decision is made according to objective standards and task constraints. Decision-making performance are generally accepted as key indicators in domain of sports officials. Accuracy in included studies expressed as number of correct decisions or percentage of correct decisions. Moreover, number and duration of fixations as the indicators of visual search are measured by eye-tracking device.

2.4 Data extraction and analysis

For the eligible research literature, we extracted data on the name of the paper, type of campaign, subject profile, number of subjects, type of indicator, mean, and standard deviation. Furthermore, we referred to MacMahon's classification to divide sports officials into interactors (with high interaction and a large number of cues to process) such as soccer referee, monitors (with low interaction and a large number of cues to monitor) such as gymnastics judge, and reactors (with low interaction and a low number of cues to track) such as tennis line judge (MacMahon et al., 2014). For those studies that conducted more than two groups of experiments (e.g., expert group, intermediate group, and non-expert group), we mainly extracted and analyzed data from the highest and lowest levels of groups. When reviewing the full text and extracting data, we applied the modified Methodological Index for Non-Randomized Studies (MINORS) to systematically assess the reliability and validity of the full text (Slim et al., 2003; Supplementary Tables 2, 3). Meta-analyses were then performed using Review Manager 5.4 to quantitatively compare the effect size (SMD: standardized mean difference) between the two groups. According to Cohen's criteria for evaluating effect sizes: an effect size <0.2 is a small effect, between 0.2 and 0.8 is a medium effect, and >0.8 is a large effect size (Rice and Harris, 2005). For each outcome, we calculated a weighted mean effect size and a 95% confidence interval (95% CI) for the mean to confirm whether the effect value was significantly different from zero. Higgins' I^2 was also calculated to measure the degree of heterogeneity in effect sizes. If $I^2 \leq 50\%$, a fixed effects model is selected; if $I^2 > 50\%$, a random-effects model is selected. In addition, publication bias was visually assessed by creating funnel plots (a simple scatter plot that reflects estimated effects of a single study with a given sample size) using Review Manager, and the risk of publication bias was further assessed by performing an Egger regression test on outcomes containing 10 or more studies using Stata 12.0. For all statistical tests, a two-sided $P < 0.05$ was considered statistically significant.

3 Result

With a systematic search of several databases, a total of 1,799 relevant studies were retrieved. After careful reading and evaluation of the full text, a total of 16 studies were selected for inclusion (Figure 1). Among the included studies, football was the most commonly sport (6 studies), followed by gymnastics (2 studies) and rugby (2 studies). While basketball, fencing, ice hockey, cricket, Behind-the-plate baseball, and fast-pitch softball had only one study. More than half of the studies examined the decision-making accuracy (10 studies), number of fixations (10 studies), and duration of fixations (10 studies) of expert and non-expert sports officials (Table 1).

3.1 Analysis of decision-making accuracy

The data of accuracy came from 10 studies involving 203 experts and 217 non-experts. After testing for heterogeneity, the heterogeneity of the studies was found to be high ($I^2 = 85\%$; $P < 0.05$), so a random effects model was chosen for the meta-analysis. The results showed a large effect size between the two groups, with an effect of 1.09 (95% CI: 0.52, 1.66; $P < 0.05$; Figure 2). It suggests that there is a significant difference in accuracy between expert and non-expert sports officials, with expert sports officials being significantly more accurate in their decision-making than non-expert sports officials. A visual assessment of the funnel plot revealed a possible publication bias (Figure 3). However, an Egger's test was performed and found that $P = 0.124$ was not statistically significant, implying that there was no publication bias.

3.2 Analysis of number of fixations

The data on the number of fixations came from 10 studies involving 158 experts and 181 non-experts. After testing for heterogeneity, it was found that there was a high degree of heterogeneity between studies ($I^2 = 80\%$; $P < 0.05$), so a random effects model was chosen for the meta-analysis. The results showed that there was a significant difference between expert and non-expert sports officials in the number of fixations, with expert sports officials having fewer fixations than non-expert sports officials. The effect size between the two groups was a medium effect, with an effect of −0.71 (95% CI: −1.25, −0.17; $P < 0.05$; Figure 4). After observing the funnel plot, it seems there might be a slight publication bias (Figure 5). However, the Egger's test indicates that a statistically insignificant P-value of 0.276 precludes the presence of publication bias.

3.3 Analysis of duration of fixations

The data on the duration of fixations came from 10 studies involving 164 experts and 193 non-experts. After testing for heterogeneity, it was found that there was a high degree of heterogeneity between studies ($I^2 = 76\%$; $P < 0.05$), so a random effects model was chosen for the meta-analysis. The results showed that there was no significant difference in duration of fixations between the expert and non-expert sports officials, with an effect size of 0.23 (95% CI: −0.25, 0.71; $P = 0.35$; Figure 6). After observing the funnel plot, it was felt that there was no publication bias (Figure 7). Egger's test was also performed and it was found that $P = 0.956$ was not statistically significant and therefore there was no publication bias.

3.4 Subgroup analysis

Sports officials were categorized into interactors, monitors and reactors according to MacMahon and Plessner (2007)'s classification, thus dividing the studies into three groups for analysis (Table 2). Among the studies included, there were 13 studies on interactors and three studies on monitors, with no studies on reactors. In the subgroup analyses we can find that there are some differences in the perceptual-cognitive skills of the various types of sports officials. In terms of accuracy, experts of interactors (SMD: 0.93; 95% CI: 0.39, 1.48) showed higher accuracy compared to non-experts. Furthermore, the difference in accuracy between experts and non-experts of monitors is greater than interactors. In terms of number of fixations, there are some differences between different types of sports officials. The experts of monitors showed fewer fixations compared to non-experts, with a medium effect size (SMD: −0.50; 95% CI: −0.91, −0.10). But there was no significant difference between the two groups of interactors (SMD: −0.75; 95% CI: −1.54, 0.03). In the terms of duration of fixations, there was no significant difference between experts and non-experts in both interactors (SMD: −0.01; 95% CI: −0.63, 0.61) and monitors (SMD: 0.66; 95% CI: −0.04, 1.35).

4 Discussion

4.1 Characteristics of difference in perceptual-cognitive skills

The purpose of this study is to systematically compare and assess the differences in perceptual-cognitive skills between expert and non-expert sports officials, and further explore the potential differences caused by different types of sports officials, in order to provide a more comprehensive understanding of the perceptual-cognitive skills of sports officials. To confirm the situation of differences between the expert and non-expert sports officials, we examined three main indicators: decision-making accuracy, number of fixations and duration of fixations. We conducted a systematic review and meta-analysis of the relevant literature to quantitatively synthesize the data from relevant studies to reveal the characteristics and reasons for the specific differences in perceptual-cognitive skills between expert and non-expert sports

TABLE 1 Characteristics and effect sizes of included studies.

References	Type of sports	Type of sport official	Number of participants	Indicator(s)	Value (mean ± SD)
1. Mascarenhas et al. (2005); (English)	Rugby	Interactors	37 (exp14, non-exp23)	Accuracy	Exp: 54.3 ± 32.9
					Non-exp: 52.4 ± 26.3
2. Bard et al. (1980); (English)	Gymnastics	Monitors	7 (exp4, non-exp3)	Number of fixations	Compulsory
					Exp: 69.44 ± 22.28
					Non-exp: 94.65 ± 16.45
					Optional
					Exp: 94.65 ± 19.38
					Non-exp: 129.41 ± 52.33
3. Aghakhanpour et al. (2021); (English)	Fencing	Monitors	28 (exp14, non-exp14)	Accuracy	Exp: 43.21 ± 3.65
					Non-exp: 27.36 ± 5.82
				Number of fixations	Exp: 2.17 ± 0.47
					Non-exp: 3.03 ± 0.40
				Duration of fixations	Exp: 642.8 ± 159.7
					Non-exp: 522.7 ± 106.7
4. Kostrna and Tenenbaum (2022); (English)	Basketball	Interactors	56 (exp24, non-exp32)	Accuracy	Exp: 61.67 ± 7.42
					Non-exp: 31.35 ± 6.33
				Number of fixations	Exp: 3.44 ± 1.11
					Non-exp: 6.85 ± 1.55
				Duration of fixations	Exp: 397.59 ± 67.41
					Non-exp: 379.11 ± 99.80
5. Mack (2020); (English)	Gymnastics	Monitors	32 (exp14, non-exp18)	Duration of fixations	Original
					Exp: 0.457 ± 0.121
					Non-exp: 0.436 ± 0.109
					Stick-figure
					Exp: 0.506 ± 0.191
					Non-exp: 0.497 ± 0.169
				Number of fixations	Original
					Exp: 6.076 ± 1.034
					Non-exp: 6.282 ± 0.892
					Stick-figure
					Exp: 5.882 ± 1.166
					Non-exp: 5.816 ± 1.300
6. Hancock and Ste-Marie (2013); (English)	Ice hockey	Interactors	30 (exp15, non-exp15)	Number of fixations	Exp: 9.19 ± 2.27
					Non-exp: 9.18 ± 2.26
				Duration of fixations	Exp: 420.31 ± 112.02
					Non-exp: 459.29 ± 148.84
				Accuracy	Exp: 19.27 ± 1.44
					Non-exp: 17.73 ± 2.31

(Continued)

TABLE 1 (Continued)

References	Type of sports	Type of sport official	Number of participants	Indicator(s)	Value (mean ± SD)
7. Ramachandran et al. (2021); (English)	Cricket	Interactors	31 (exp12, non-exp19)	Number of fixations	Exp: 5.0 ± 1.6
					Non-exp: 4.2 ± 1.7
				Duration of fixations	Exp: 972.91 ± 628.01
					Non-exp: 1,520.42 ± 663.90
8. Van Biemen et al. (2023); (English)	Football	Interactors	14 (exp5, non-exp9)	Accuracy	Exp: 87.8 ± 10.6
					Non-exp: 76.1 ± 14.7
				Duration of fixations	Exp: 400 ± 18
					Non-exp: 507 ± 12
9. Larkin et al. (2011); (English)	Football	Interactors	28 (exp15, non-exp13)	Accuracy	Exp: 23.7 ± 4.8
					Non-exp: 21.9 ± 4.2
10. Moore et al. (2019); (English)	Rugby	Interactors	18 (exp9, non-exp9)	Accuracy	Exp: 53.33 ± 14.14
					Non-exp: 38.89 ± 13.64
				Number of fixations	Exp: 1.64 ± 0.29
					Non-exp: 2.20 ± 0.19
11. Millslagle et al. (2013a); (English)	Behind-the-plate baseball	Interactors	8 (exp4, non-exp4)	Duration of fixations	Exp: 85.7% ± 14.3
					Non-exp: 49.8% ± 11.4
12. Spitz et al. (2018); (English)	Football	Interactors	43 (exp22, non-exp21)	Accuracy	Exp: 63.1 ± 9.8
					Non-exp: 55.4 ± 9.6
13. Millslagle et al. (2013b); (English)	Fast pitch softball	Interactors	8 (exp4, non-exp4)	Number of fixations	Exp: 2.06 ± 1.6
					Non-exp: 2.59 ± 1.8
14. Catteeuw et al. (2009); (English)	Football	Interactors	10 (exp5, non-exp5)	Accuracy	Exp: 83.5 ± 7.0
					Non-exp: 74.6 ± 4.8
15. Spitz et al. (2016); (English)	Football	Interactors	39 (exp20, non-exp19)	Accuracy	Open play technical
					Exp: 54.5 ± 19.2
					Non-exp: 49.5 ± 13.5
					Open play disciplinary
					Exp: 61.0 ± 17.0
					Non-exp: 45.3 ± 16.1
					Corner kick technical
					Exp: 69.5 ± 13.0
					Non-exp: 56.8 ± 10.5
					Corner kick disciplinary
					Exp: 82.5 ± 5.4
					Non-exp: 82.6 ± 7.4

(Continued)

TABLE 1 (Continued)

References	Type of sports	Type of sport official	Number of participants	Indicator(s)	Value (mean ± SD)
				Number of fixations	Open play
					Exp: 16.9 ± 2.7
					Non-exp: 17.2 ± 2.6
					Corner kick
					Exp: 19.1 ± 2.2
					Non-exp: 19.6 ± 2.6
16. Van Biemen et al. (2022); (English)	Football	Interactors	12 (exp4, non-exp8)	Number of fixations	Exp: 1.3 ± 0.2
					Non-exp: 1.8 ± 0.3
				Duration of fixations	Exp: 1,158 ± 150
					Non-exp: 847 ± 240

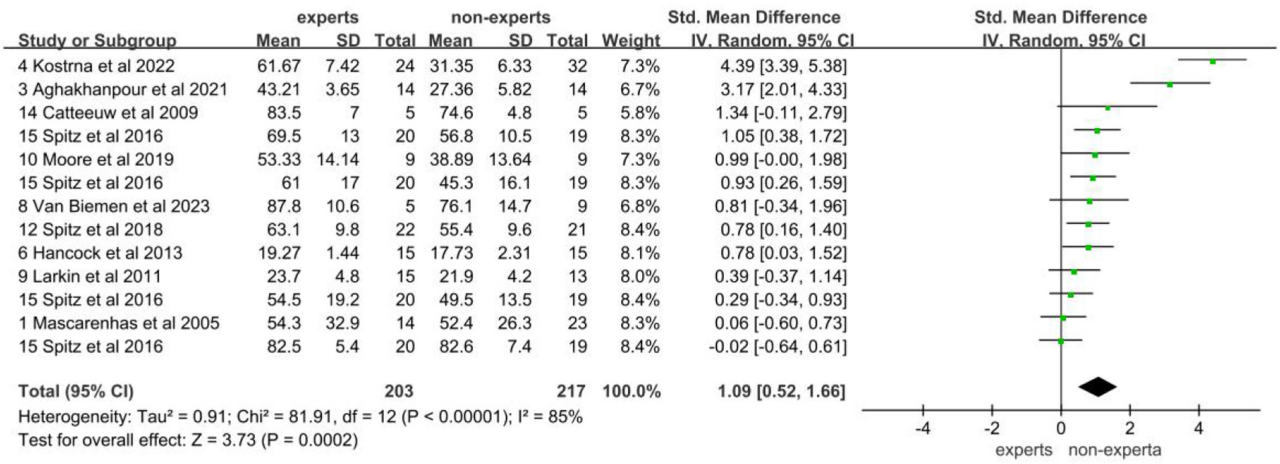

FIGURE 2
Forest plot of decision-making accuracy.

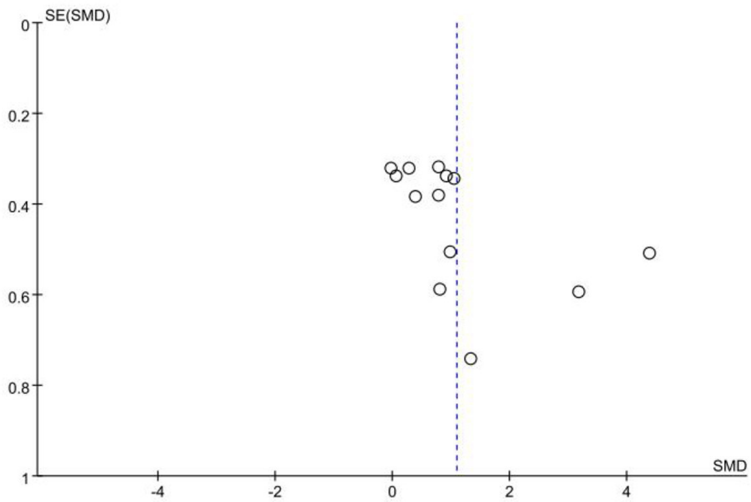

FIGURE 3
Funnel plot of decision-making accuracy.

Study or Subgroup	experts Mean	experts SD	experts Total	non-experts Mean	non-experts SD	non-experts Total	Weight	Std. Mean Difference IV, Random, 95% CI
7 Ramachandran et al 2021	5	1.6	12	4.2	1.7	19	8.7%	0.47 [-0.26, 1.20]
5 Mack 2020	5.882	1.166	14	5.816	1.3	18	8.9%	0.05 [-0.65, 0.75]
6 Hancock et al 2013	9.19	2.27	15	9.18	2.26	15	8.8%	0.00 [-0.71, 0.72]
15 Spitz et al 2016	16.9	2.7	20	17.2	2.6	19	9.1%	-0.11 [-0.74, 0.52]
15 Spitz et al 2016	19.1	2.2	20	19.6	2.6	19	9.1%	-0.20 [-0.83, 0.43]
5 Mack 2020	6.076	1.034	14	6.282	0.892	18	8.9%	-0.21 [-0.91, 0.49]
13 Millslagle et al 2013	2.06	1.6	4	2.59	1.8	4	6.1%	-0.27 [-1.67, 1.13]
2 Bard et al 1980	94.65	19.38	4	129.41	52.33	3	5.4%	-0.81 [-2.43, 0.82]
2 Bard et al 1980	69.44	22.28	4	94.65	16.45	3	5.1%	-1.05 [-2.77, 0.66]
3 Aghakhanpour et al 2021	2.17	0.57	14	3.03	0.48	14	8.2%	-1.58 [-2.45, -0.72]
16 van Biemen et al 2022	1.3	0.2	4	1.8	0.3	8	5.9%	-1.69 [-3.14, -0.23]
10 Moore et al 2019	1.64	0.29	9	2.2	0.19	9	6.8%	-2.18 [-3.40, -0.95]
4 Kostrna et al 2022	3.44	1.11	24	6.85	1.55	32	8.8%	-2.44 [-3.14, -1.73]
Total (95% CI)			**158**			**181**	**100.0%**	**-0.71 [-1.25, -0.17]**

Heterogeneity: Tau² = 0.73; Chi² = 59.07, df = 12 (P < 0.00001); I² = 80%

Test for overall effect: Z = 2.57 (P = 0.01)

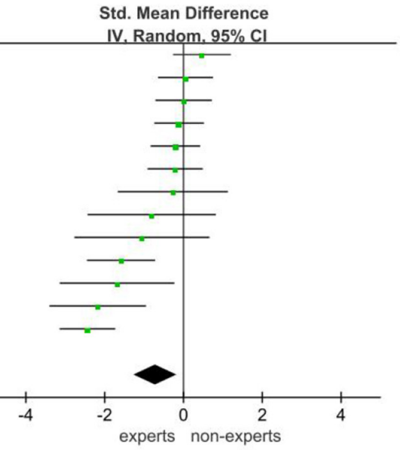

FIGURE 4
Forest plot of number of fixations.

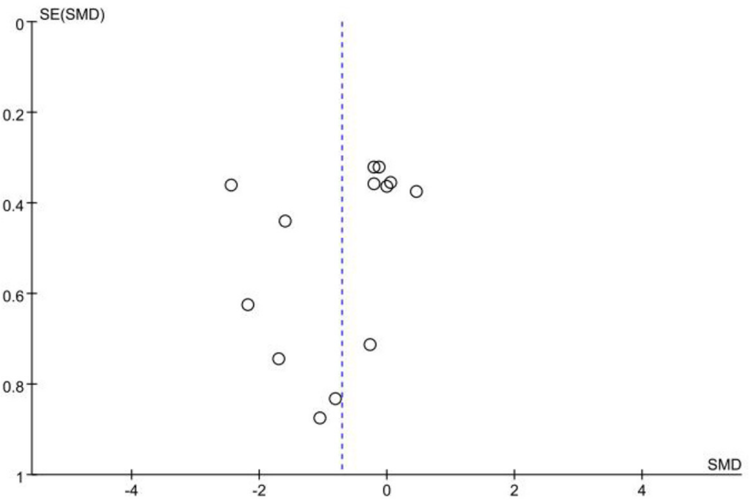

FIGURE 5
Funnel plot of number of fixations.

officials. The results of the study showed that there was a significant difference between expert and non-expert sports officials in terms of decision-making accuracy and number of fixations, but not in terms of duration of fixations.

Accuracy directly reflects the sports officials' competence and level of performance, and is a direct indicator for evaluating sports officials. The findings on accuracy are similar to the previous studies, and many researchers have confirmed that expert sports officials are more accurate than non-expert sports officials when making decisions (Spitz et al., 2018; Moore et al., 2019). We found that expert sports officials were significantly more accurate than non-expert sports officials and had a large effect sizes, suggesting that expert sports officials are able to use their expertise to make more accurate decisions based on objective criteria when officiating. Aghakhanpour et al. (2021) found that the number of correct decisions made by expert sports officials was significantly higher than novice sports officials, and argue that the time and experience that expert sports officials have gained over the years can help them to pick up a number of favorable cues by observing the movements of the athletes. Kostrna and Tenenbaum (2022) also argued that expert sports officials are able to develop better mental representations and more effective information processing strategies through training, resulting in more accurate decisions than novice sports officials. Taken together, accuracy seem to serve as an important indicator for measuring and distinguishing expert sports officials from non-expert sports officials.

The number of fixations reflects the sports official's proficiency in the perceptual task as well as the level of visual information collection and stability of visual control, with fewer fixations indicating that the sports official is more efficient at extracting information. The results demonstrate that the number of fixations made by expert sports officials is significantly lower than that of

Study or Subgroup	experts Mean	experts SD	experts Total	non-experts Mean	non-experts SD	non-experts Total	Weight	Std. Mean Difference IV, Random, 95% CI
11 Millslagle et al 2013	85.7	14.3	4	49.8	11.4	4	3.5%	2.41 [0.25, 4.58]
3 Aghakhanpour et al 2021	295.8	74.6	14	194.02	35.9	14	8.3%	1.69 [0.81, 2.57]
16 van Biemen et al 2022	1,158	150	4	847	240	8	6.0%	1.32 [-0.04, 2.69]
3 Aghakhanpour et al 2021	642.8	159.7	14	522.7	106.7	14	8.8%	0.86 [0.08, 1.64]
13 Millslagle et al 2013	448.07	108.02	4	360.85	120.63	4	5.6%	0.66 [-0.80, 2.12]
4 Kostrna et al 2022	397.59	67.41	24	379.11	99.8	32	10.1%	0.21 [-0.32, 0.74]
5 Mack 2020	0.457	0.121	14	0.436	0.109	18	9.3%	0.18 [-0.52, 0.88]
5 Mack 2020	0.506	0.191	14	0.497	0.169	18	9.3%	0.05 [-0.65, 0.75]
15 Spitz et al 2016	0.32	0.04	20	0.32	0.09	19	9.6%	0.00 [-0.63, 0.63]
15 Spitz et al 2016	0.4	0.09	20	0.4	0.09	19	9.6%	0.00 [-0.63, 0.63]
6 Hancock et al 2013	420.31	112.02	15	459.29	148.84	15	9.1%	-0.29 [-1.01, 0.43]
7 Ramachandran et al 2021	972.91	628.01	12	1,520.42	663.9	19	9.0%	-0.82 [-1.57, -0.06]
8 Van Biemen et al 2023	400	18	5	507	12	9	1.8%	-7.01 [-10.27, -3.76]
Total (95% CI)			**164**			**193**	**100.0%**	**0.23 [-0.25, 0.71]**

Heterogeneity: Tau² = 0.53; Chi² = 49.30, df = 12 (P < 0.00001); I² = 76%
Test for overall effect: Z = 0.93 (P = 0.35)

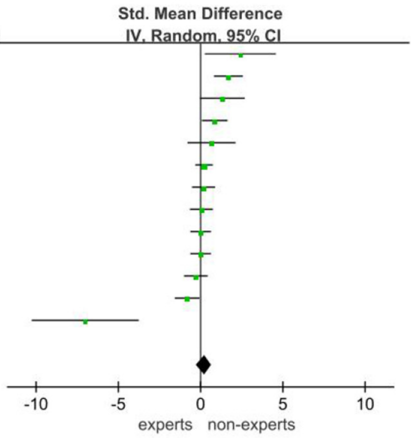

FIGURE 6
Forest plot of duration of fixations.

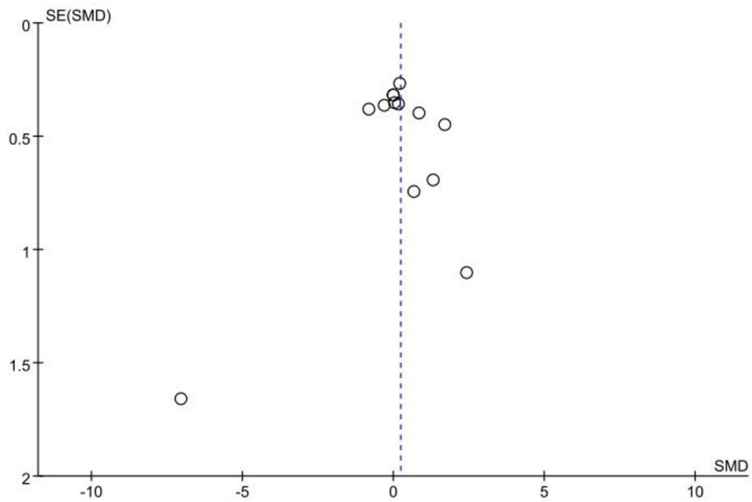

FIGURE 7
Funnel plot of duration of fixations.

non-expert sports officials, implying that expert sports officials employ a more efficient visual search strategy. In the field of cognitive psychology, the strategy of visual search has long been an important tool to study the cognitive characteristics (Wilschut et al., 2014). In the study of athletes' visual search strategies, it was discovered that the number of fixations decreased as the level of athleticism increased. The reduction in the number of fixations by expert athletes is related to the perceptual-cognitive advantage they have developed over long periods of training and competition (Williams et al., 2012). This perceptual-cognitive advantage enabled expert athletes to conduct effective visual searches, thus focusing on the important and critical areas of information in the motor situation, which ultimately leads to fewer number of fixations. Similarly for sports officials, such a perceptual-cognitive advantage increases with the sports officials' level of officiating, resulting in fewer fixations and more efficient information extraction.

However, the result of duration of fixations in this study did not show significant differences and do not support the previously stated hypothesis that expert sports officials have longer duration of fixations. The duration of fixations reflects the efficiency of the sports official's attention allocation and information processing. Typically, longer duration of fixations result in greater extraction of information from the target, facilitating more accurate and rational decision-making. It has been suggested that the fixations of expert sports officials is characterized by longer duration, indicating that they are able to extract more relevant task information from each fixation (Mann et al., 2007). However, this conclusion is not always corroborated. As the perceptual-cognitive strategies of novice sports officials are not well-developed, it often takes longer duration of fixations to extract the information for making a decision (Mann et al., 2019). There is research even indicating that high sustained attention are not crucial skills and are not important for expert sports officials (Spitz et al., 2018). This also means that duration of fixations is not yet a valid indicator for distinguishing between expert and non-expert sports officials.

4.2 Reason of difference in perceptual-cognitive skills

MacMahon et al. (2014) had composed a decision-making model for sports officials and argued that perception is the first step in the whole decision-making process, followed by information categorization and integration, and finally the appropriate decision is made. The sports officials must continually perceive the information on the field of play (including the environment, athletes, and even colleagues), and use specific visual search strategies to collect relevant information while ignoring irrelevant information that may disrupt decision-making (Helsen and Bultynck, 2004). It is indisputable that the sport official's perceptual-cognitive skills, as a crucial element of early information collection in the decision-making process, are critical to make accurate and efficient decisions.

The results of the study show that there are significant differences in accuracy and the number of fixations between expert and non-expert sports officials, indicating the variance in their perceptual-cognitive skills. The perceptual-cognitive advantage possessed by expert sports officials can assist them in making more accurate decisions and optimizing their visual search strategy when officiating to some degree. In recent years, researchers have extensively utilized eye-tracking device to investigate the perceptual-cognitive skills of sports officials, trying to determine the primary factors causing differences in such skills. After conducting a systematic review of relevant literature, we propose four potential factors that may influence the perceptual-cognitive skills of sports officials.

Firstly, we argue that task anticipation behavior of sports officials leads to differences in information perception. Expert sports officials can exhibit more superior perceptual-cognitive skills than non-expert sports officials due to their abundant reserves of professional expertise and extensive experience. Having accumulated such experience, expert sports officials are able to generate specific knowledge and perceptual skills in the areas they are familiar with, which facilitate the gathering and processing of information in their officiating process. This ability not only helps them to make better decisions, but also to make efficient and accurate anticipations (Ericsson and Kintsch, 1995). Anticipation is the act of expecting or predicting what may happen in the future based on prior knowledge, experience, or intuition. It has been shown that anticipation allows experts to expend fewer resources and use more effective visual search strategies to scan relevant environmental information (Mann et al., 2007). Expert athletes can alleviate the time constraints of the task by making faster and more accurate decisions than non-experts through their outstanding predictions. Likewise, expert sports officials also can perceive and process information on the field of play earlier with the help of anticipation (Williams et al., 2002). As a result, sports officials can direct their vision earlier, concentrating on zones where potential fouls may occur, ultimately decreasing the number of fixations and improving decision-making accuracy. In contrast, non-expert sports officials displayed limited knowledge and experience, leading to extensive information gathering through various visual search behavior. This in turn resulted in more fixations and lower efficiency in collecting information, ultimately lowering decision-making accuracy.

Secondly, we argue that different methods of memory retrieval lead to differences in information processing. When officiating, sports officials sometimes draw on their own memories of previous events to generate responses that help them to better perceive and process information. Previous research has shown that experts appear to be able to retain experience and knowledge from training and competition in long-term memory. They can quickly extract information when necessary to perform actions with speed and accuracy (Ericsson and Chase, 1982). Plessner and Haar (2006) in their finding of OSDMM (Official's Specific Decision-Making Model) also mentioned that the process of decision-making by sport official begins with the official perceiving the stimulus. Next, the stimulus is encoded, interpreted, and categorized, assisted by long-term memory. Then, the sports officials integrates the perceived stimulus and information with their retrieved memories and any additional information into decision-making. Furthermore, as performers become more expert, they have been shown to be able to use their working memory more effectively (Ericsson, 2008). As expert sports officials will usually have more experience, they will develop more refined information retrieval strategies and processing methods. Expert sports officials are able to extract relevant information from long-term memory more efficiently when confronted with comparable situations, directing their visual attention and making accurate decisions. Thus, expert sports officials demonstrate fewer fixations and higher decision-making accuracy. In contrast, non-expert sports officials have less officiating experience, limited content stored in long-term memory, and rely on more random visual behavior to collect information when faced with unfamiliar and complex tasks.

Thirdly, we argue that information reduction strategy lead to differences in sources of information. Some scholars have attempted to explain differences in perceptual-cognitive skills between experts and non-experts using the information-reduction hypothesis (Haider and Frensch, 1999). This hypothesis suggests that experts are able to optimize the amount of information processed through selective gaze behavior, ignoring task-irrelevant information and actively focusing on task-relevant information. In most sports, sports officials are often required to make accurate and reasonable decisions in a relatively short period of time, but complex tasks and time constraints can make sports officials' decision-making behavior extremely difficult. In such time-constrained tasks, experts are better able to distinguish between relevant and irrelevant sources of information and focus their attention on the most important sources of information (Brams et al., 2019). Expert sports officials have learned over many years of officiating experience to use targeted visual search strategies to ignore irrelevant cues in the task, selectively focusing on task-relevant information to reduce and optimize the amount of information they have to process. The lower number of fixations demonstrated by experts is because they reduce the information-processing load and minimize the need for sensory input to create a coherent perception of the task situation (Aghakhanpour et al., 2021).

TABLE 2 Results of subgroup analyses.

Variable	Type of sports officials	Number of studies	SMD (95% CI)	*P*-value	I^2 (*P*)
Decision-making accuracy	Interactors	9	0.93 [0.39, 1.48]	$P < 0.05$	83% ($P < 0.05$)
	Monitors	1	3.17 [2.01, 4.33]	$P < 0.05$	/
Number of fixations	Interactors	7	−0.75 [−1.54, 0.03]	$P = 0.06$	86% ($P < 0.05$)
	Monitors	3	−0.50 [−0.91, −0.10]	$P < 0.05$	58% ($P = 0.05$)
Duration of fixations	Interactors	8	−0.01 [−0.63, 0.61]	$P = 0.96$	76% ($P < 0.05$)
	Monitors	2	0.66 [−0.04, 1.35]	$P = 0.06$	70% ($P < 0.05$)

Fourthly, it has been proposed that differences in perceptual-cognitive skills are linked to the particular sport and task nature. The perceptual-cognitive demands on sports officials vary from sport to sport. In order to reduce the impact of item differences, we used MacMahon's classification of sports officials to further compare and analyze the perceptual-cognitive skills of expert and non-expert sports officials (MacMahon and Plessner, 2007). MacMahon categorized sports officials into interactors, monitors, and reactors based on two main aspects: the amount of interaction with athletes and movement demands, and in the number of cues being observed. Interactors with high interaction and physical movement demands and often a large number of cues to process, such as soccer and basketball referees. Monitors with low to medium interaction and physical demands, but often a medium to large number of cues to monitor, such as volleyball and gymnastics judges. Reactors with low interaction and movement demands and a low to medium number of cues to track, such as tennis line judges. Among these three categories of sports officials, reactors make judgment based on objective facts without any involvement of perceptual-cognitive skills in the process of adjudication. As a result, there is limited academic research on the perceptual-cognitive skills of reactor, and we will not discuss this type of sports official in our study. Our findings confirm that the type of sports officials does not affect accuracy and duration of fixations. However, accuracy can be used as a useful parameter to differentiate between expert and non-expert decision-making performance, while duration of fixation does not. The results concerning number of fixations indicate that interactors and monitors exhibit different perceptual-cognitive skills due to the task's particular nature. Interactors need to pay attention to a large number of different targets and cues, in addition to frequent movements and interactions during officiating. This also renders the visual search task of such sports officials more intricate, with greater uncertainty in decision-making. In conclusion, differences in sports do result in differences in the perceptual-cognitive skills of sports officials. Therefore, the specifics of the sport need to be taken into account when evaluating the perceptual-cognitive skills of sports officials.

Furthermore, differences in perceptual-cognitive skills of sports officials may also be influenced by other factors. Such as the type of stimulus and the presentation of decision clips. Different types of stimuli and presentation may cause sports officials to perceive and extract different information when watching the materials. This study focuses on the potential impact of the types of sports officials, but future studies are needed to explore the effects of other factors on the perceptual-cognitive skills of expert and non-expert sports officials.

5 Conclusion

This study employed meta-analysis to comprehensively analyze and compare the perceptual-cognitive skills of expert and non-expert sports officials. The results of the study show that accuracy can be an important indicator of perceptual-cognitive skills in distinguishing expert and non-expert sports officials. Number of fixations can be important factors of perceptual-cognitive skills in distinguishing between experts and non-experts in sport monitors, and the perceptual-cognitive skills of experts are significantly better than those of non-experts in this type of sports official. As MacMahon states, perceptual-cognitive skills are crucial in sports officials and are being emphasized by a growing number of scholars. The training and development of sports officials can try to start from the perceptual-cognitive skills to improve the efficiency of sports officials in information collection and processing, thus helping them to make timely and accurate decisions more efficiently.

6 Limitations and future directions

This study has the following three limitations. Firstly, the sample size included in the study was limited, which to some extent may have made the results statistically insignificant. Secondly, the inclusion of multiple sports in this study and the different definitions of "expert" and "non-expert" sports officials in different studies resulted in a high degree of heterogeneity between the included studies. Although we used MacMahon's classification of sports officials to group the studies, we could not completely eliminate the heterogeneity between studies. Thirdly, most of the studies included in this review were tested in a laboratory setting, and the data collected may have differed from reality. Future research into the perceptual-cognitive skills of sports officials can be considered in the following areas. Firstly, different eye movement indicators were selected as outcome variables to further explore the characteristics of sports officials' gaze behavior. Secondly, a specific sport was used as the object of the study to explore the differences in perceptual-cognitive skills of different sports officials in the same sport. Thirdly, other potential factors that may influence the perceptual-cognitive skills of expert sports officials, such as the testing environment, measurement tools and presentation of clips, can be further explored.

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

YW: Conceptualization, Formal analysis, Methodology, Project administration, Writing – original draft, Writing – review & editing. ZY: Formal analysis, Investigation, Writing – review & editing. RW: Formal analysis, Investigation, Writing – review & editing. HZ: Methodology, Supervision, Writing – review & editing. QZ: Conceptualization, Funding acquisition, Project administration, Writing – review & editing, Writing – original draft.

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Supplementary material

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References

Abernethy, B., and Russell, D. G. (1987). Expert-novice differences in an applied selective attention task. *J. Sport. Exer. Psy.* 9, 326–345. doi: 10.1123/jsp.9.4.326

Abernethy, B., Zawi, K., and Jackson, R. C. (2008). Expertise and attunement to kinematic constraints. *Perception* 37, 931–948. doi: 10.1068/p5340

Aghakhanpour, N. B., Abdoli, B., Farsi, A., and Moeinirad, S. (2021). Comparison of visual search behavior and decision-making accuracy in expert and novice fencing referees. *Optometr. Vis. Sci.* 98, 783–788. doi: 10.1097/opx.0000000000001726

Allard, F., Graham, S., and Paarsalu, M. E. (1980). Perception in sport: basketball. *J. Sport. Exer. Psy.* 2, 14–21. doi: 10.1123/jsp.2.1.14

Bard, C., Fleury, M., Carrière, L., and Hallé, M. (1980). Analysis of gymnastics judges' visual search. *Res. Q. Exer. Sport.* 51, 267–273. doi: 10.1080/02701367.1980.10605195

Bar-Eli, M., Plessner, H., and Raab, M. (2011). *Judgment, Decision-Making and Success in Sport, Vol. 1.* Hoboken, NJ: John Wiley & Sons.

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. doi: 10.1037/bul0000207

Catteeuw, P., Helsen, W., Gilis, B., Van Roie, E., and Wagemans, J. (2009). Visual scan patterns and decision-making skills of expert assistant referees in offside situations. *J. Sport. Exer. Psy.* 31, 786–797. doi: 10.1123/jsep.31.6.786

Ericsson, K. A. (2008). Deliberate practice and acquisition of expert performance: a general overview. *Acad. Emerg. Med.* 15, 988–994. doi: 10.1111/j.1553-2712.2008.00227.x

Ericsson, K. A., and Chase, W. G. (1982). Exceptional memory: extraordinary feats of memory can be matched or surpassed by people with average memories that have been improved by training. *Am. Sci.* 70, 607–615.

Ericsson, K. A., and Kintsch, W. (1995). Long-term working memory. *Psychol. Rev.* 102:211. doi: 10.1037/0033-295X.102.2.211

Guizani, S. M., Bouzaouach, I., Tenenbaum, G., and Kheder, A. B. (2006). Simple and choice reaction times under varying levels of physical load in high skilled fencers. *J. Sport. Med. Phys. Fit.* 46:344.

Haider, H., and Frensch, P. A. (1999). Eye movement during skill acquisition: more evidence for the information-reduction hypothesis. *J. Exp. Psychol. Learn.* 25:172. doi: 10.1037/0278-7393.25.1.172

Hancock, D. J., and Ste-Marie, D. M. (2013). Gaze behaviors and decision making accuracy of higher-and lower-level ice hockey referees. *Psychol. Sport. Exerc.* 14, 66–71. doi: 10.1016/j.psychsport.2012.08.002

Helsen, W., and Bultynck, J. B. (2004). Physical and perceptual-cognitive demands of top-class refereeing in association football. *J. Sport Sci.* 22, 179–189. doi: 10.1080/02640410310001641502

Helsen, W., and Pauwels, J. M. (1993). The relationship between expertise and visual information processing in sport. *Adv. Psychol.* 102, 109–134. doi: 10.1016/S0166-4115(08)61468-5

Helsen, W. F., and Starkes, J. L. (1999). A multidimensional approach to skilled perception and performance in sport. *Appl. Cogn. Psych.* 13, 1–27. doi: 10.1002/(SICI)1099-0720(199902)13:1<1::AID-ACP540>3.0.CO;2-T

Kittel, A., Cunningham, I., Larkin, P., Hawkey, M., and Rix-Lièvre, G. (2021). Decision-making training in sporting officials: past, present and future. *Psychol. Sport. Exerc.* 56:102003. doi: 10.1016/j.psychsport.2021.102003

Kostrna, J., and Tenenbaum, G. (2022). Developing and testing the expanded sport official's decision-making model. *Int. J. Sport. Exerc. Psychol.* 20, 586–611. doi: 10.1080/1612197x.2021.1891117

Larkin, P., Berry, J., Dawson, B., and Lay, B. (2011). Perceptual and decision-making skills of Australian football umpires. *Int. J. Perf. Anal. Spor.* 11, 427–437. doi: 10.1080/24748668.2011.11868562

Mack, M. (2020). Exploring cognitive and perceptual judgment processes in gymnastics using essential kinematics information. *Adv. Cogn. Psychol.* 16:34. doi: 10.5709/acp-0282-7

MacMahon, C., Mascarenhas, D., Plessner, H., Pizzera, A., Oudejans, R., and Raab, M. (2014). *Sports Officials and Officiating: Science and Practice*. London: Routledge.

MacMahon, C., and Plessner, H. (2007). "The sport official in research and practice," in *Developing Sport Expertise*, eds. D. Farrow, J. Baker, and C. MacMahon (London: Routledge), 194–214.

Mann, D. L., Causer, J., Nakamoto, H., and Runswick, O. R. (2019). Visual search behaviors in expert perceptual judgements. *Anticipat. Decision Mak. Sport* 4, 59–78. doi: 10.4324/9781315146270-4

Mann, D. L., Farrow, D., Shuttleworth, R., Hopwood, M., and MacMahon, C. (2009). The influence of viewing perspective on decision-making and visual search behaviour in an invasive sport. *Int. J. Sport. Psychol.* 40, 546–564.

Mann, D. T., Williams, A. M., Ward, P., and Janelle, C. M. (2007). Perceptual-cognitive expertise in sport: a meta-analysis. *J. Sport. Exercise. Psy.* 29, 457–478. doi: 10.1123/jsep.29.4.457

Marteniuk, R. G. (1976). *Information Processing in Motor Skills*. New York, NY: Holt, Rinehart and Winston.

Mascarenhas, D. R., Collins, D., and Mortimer, P. (2005). The accuracy, agreement and coherence of decision-making in rugby union officials. *J. Sport. Behav.* 28:131. doi: 10.1123/tsp.19.2.131

Millslagle, D. G., Hines, B. B., and Smith, M. S. (2013a). Quiet eye gaze behavior of expert, and near-expert, baseball plate umpires. *Percept. Motor. Skill.* 116, 69–77. doi: 10.2466/24.22.27.PMS.116.1.69-77

Millslagle, D. G., Smith, M. S., and Hines, B. B. (2013b). Visual gaze behavior of near-expert and expert fast pitch softball umpires calling a pitch. *J. Strength. Cond. Res.* 27, 1188–1195. doi: 10.1519/JSC.0b013e318269ab15

Moeinirad, S., Abdoli, B., Farsi, A., and Ahmadi, N. (2020). The role of quiet eye duration and its components in a complex far-aiming task. *J. Motor. Learn. Dev.* 8, 516–527. doi: 10.1123/jmld.2019-0048

Moore, L. J., Harris, D. J., Sharpe, B. T., Vine, S. J., and Wilson, M. R. (2019). Perceptual-cognitive expertise when refereeing the scrum in rugby union. *J. Sport. Sci.* 37, 1778–1786. doi: 10.1080/02640414.2019.1594568

Ottoboni, G., Russo, G., and Tessari, A. (2015). What boxing-related stimuli reveal about response behaviour. *J. Sport. Sci.* 33, 1019–1027. doi: 10.1080/02640414.2014.977939

Panchuk, D., and Vickers, J. N. (2006). Gaze behaviors of goaltenders under spatial-temporal constraints. *Hum. Mov. Sci.* 25, 733–752. doi: 10.1016/j.humov.2006.07.001

Piras, A., Lobietti, R., and Squatrito, S. (2014). Response time, visual search strategy, and anticipatory skills in volleyball players. *J. Ophthalmol.* 2014:7. doi: 10.1155/2014/189268

Plessner, H., and Haar, T. (2006). Sports performance judgments from a social cognitive perspective. *Psychol. Sport. Exerc.* 7, 555–575. doi: 10.1016/j.psychsport.2006.03.007

Ramachandran, P., Watts, M., Jackson, R. C., Hayes, S. J., and Causer, J. (2021). Howzat! Expert umpires use a gaze anchor to overcome the processing demands of leg before wicket decisions. *J. Sport. Sci.* 39, 1936–1943. doi: 10.1080/02640414.2021.1908734

Rice, M. E., and Harris, G. T. (2005). Comparing effect sizes in follow-up studies: ROC area, Cohen's *d*, and r. *Law. Human. Behav.* 29, 615–620. doi: 10.1007/s10979-005-6832-7

Schrödter, R., Schwarting, A., Fasold, F., Schul, K., and Klatt, S. (2023). The relevance of general spatial anticipation skills for basketball referees. *Appl. Sci.* 13:2991. doi: 10.3390/app13052991

Slim, K., Nini, E., Forestier, D., Kwiatkowski, F., Panis, Y., and Chipponi, J. (2003). Methodological index for non-randomized studies (MINORS): development and validation of a new instrument. *Anz. J. Surg.* 73, 712–716. doi: 10.1046/j.1445-2197.2003.02748.x

Spitz, J., Put, K., Wagemans, J., Williams, A. M., and Helsen, W. F. (2016). Visual search behaviors of association football referees during assessment of foul play situations. *Cogn. Res.* 1, 1–11. doi: 10.1186/s41235-016-0013-8

Spitz, J., Put, K., Wagemans, J., Williams, A. M., and Helsen, W. F. (2018). The role of domain-generic and domain-specific perceptual-cognitive skills in association football referees. *Psychol. Sport. Exerc.* 34, 47–56. doi: 10.1016/j.psychsport.2017.09.010

Van Biemen, T., Oudejans, R. R. D., Savelsbergh, G. J. P., Zwenk, F., and Mann, D. L. (2023). Into the eyes of the referee: a comparison of elite and sub-elite football referees'on-field visual search behaviour when making foul judgements. *Int. J. Sports. Sci. Coa.* 18, 78–90. doi: 10.1177/17479541211069469

Van Biemen, T., van Zanten, T. F., Savelsbergh, G. J. P., and Mann, D. L. (2022). "What needs to be seen": an exploration into the visual anticipation behaviour of different skill-level football referees while observing long passes on-field. *Hum. Mov. Sci.* 85:102980. doi: 10.1016/j.humov.2022.102980

Vickers, J. N., and Adolphe, R. M. (1997). Gaze behaviour during a ball tracking and aiming skill. *Int. J. Sports. Vis.* 4, 8–27.

Ward, P., and Williams, A. M. (2003). Perceptual and cognitive skill development in soccer: the multidimensional nature of expert performance. *J. Sport. Exer. Psy.* 25, 93–111. doi: 10.1123/jsep.25.1.93

Williams, A. M., Davids, K., Burwitz, L., and Williams, J. G. (1994). Visual search strategies in experienced and inexperienced soccer players. *Res. Q. Exer. Sport.* 65, 127–135. doi: 10.1080/02701367.1994.10607607

Williams, A. M., and Ericsson, K. A. (2005). Perceptual-cognitive expertise in sport: some considerations when applying the expert performance approach. *Hum. Mov. Sci.* 24, 283–307. doi: 10.1016/j.humov.2005.06.002

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. Psych.* 25, 432–442. doi: 10.1002/acp.1710

Williams, A. M., Singer, R. N., and Frehlich, S. G. (2002). Quiet eye duration, expertise, and task complexity in near and far aiming tasks. *J. Motor. Behav.* 34, 197–207. doi: 10.1080/00222890209601941

Williams, A. M., Ward, P., Bell-Walker, J., and Ford, P. R. (2012). Perceptual-cognitive expertise, practice history profiles and recall performance in soccer. *Br. J. Psychol.* 103, 393–411. doi: 10.1111/j.2044-8295.2011.02081.x

Wilschut, A., Theeuwes, J., and Olivers, C. N. (2014). Priming and the guidance by visual and categorical templates in visual search. *Front. Psychol.* 5:148. doi: 10.3389/fpsyg.2014.00148

Ziv, G., Lidor, R., Zach, S., Brams, S., and Helsen, W. F. (2020). Gaze behavior of referees in sport-a review. *Front. Sports. Act. Liv.* 2:146. doi: 10.3389/fspor.2020.572891

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The effects of age and gender and elite levels on perceptual–cognitive skills of adolescent badminton athletes

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Introduction: This study aimed to examine perceptual-cognitive skills across age, gender and elite levels of badminton adolescent athletes.

Methods: A total of 57 badminton athletes divided into junior high school athletes (age = 13.36 ± 1.14 years, females = 22, males = 11) and senior high school athletes (age = 16.25 ± 0.84 years, females = 11, males = 13) were evaluated using a cognitive component skills approach. Elite levels were classified as semi-elite (n = 29, score = 3.23) and competitive elite (n = 28, score = 5.84) levels. Each group completed a cognitive test, including an evaluation of their capacity for Corsi block-tapping (CCT) and spatial priming tasks (SPT).

Results: No gender effects were found in the perceptual skills of the adolescent players, and the age effect was consistent across gender. For the elite levels, the perceptual-cognitive skills of SPT of reaction time was performed equally in the groups of semi-elite and competitive players, however, in the CCT Span of working-memory (WM), competitive-elite players outperformed semi-elite players.

Conclusion: We found that perceptual-cognitive skills of WM play crucial roles in the open-skill sports of badminton. Thus, when developing advanced skills to higher elite levels in adolescent players, perceptual-cognitive skills should be considered.

KEYWORDS

information processing, reaction time, working-memory, adolescent, perceptual-cognitive

1 Introduction

Elite athletes typically exhibit superior perceptual and cognitive skills compared to semi-elite athletes or nonathletes owing to the physical training and cognitive stimulation provided by sports (Alves et al., 2013). Elite athletes gain a competitive edge by developing cognitive skills and strategies through deliberate practice, enhancing their ability to process information more efficiently (Eccles, 2006; Ericsson, 2006; Furley et al., 2015). Studies conducted over time have shown that sports experts have greater perceptual-cognitive skills in picking up information (Mann et al., 2007). Furthermore, types of sports in terms of open or closed skills (Schmidt et al., 2018) may affect neurocognition, which is a crucial element for efficient elite levels (Eccles, 2006; Ericsson, 2006; Furley P. and Memmert, 2010), specifically in open-skill

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sports, the distinctive neurocognitive changes are induced by sports types (Mann et al., 2007; Tsai et al., 2017; Hung et al., 2018). Badminton, classified as an open-skill sport (Goodway et al., 2021), can be mastered at the elite level by refining various stroke strategies. This sport demands rapid judgment, which in turn fine-tunes the tactical decision-making process of the human brain, thereby optimizing performance. This allows confident decisions to be made within seconds (Shaw, 1989). In perceptual and cognitive studies relative to badminton, Jin et al. (2011) suggested that badminton players have higher C1 wave amplitudes, reflecting their correct decision-making and anticipatory abilities. Wang et al. (2015) argued that badminton players perform better in basic visuospatial cognitive operations than nonathletes. Furthermore, Hung et al. (2018) studied acute running and badminton exercises and found that badminton exercise has a relative impact on Brain-Derived Neurotrophic Factor (BDNF) and executive function.

Similar to other sports, badminton success requires both physical and perceptual abilities. Advanced perceptual skills must be developed to ensure that the execution of skills is both effective and proficient, one needs to have advanced perceptual skills (Mori et al., 2002). Recent studies and theoretical developments in the fields of cognitive science and neuroscience have identified positive correlations between complex cognitive functions and attention, selective attention, and working-memory (WM) (Kane et al., 2001; Kane and Engle, 2003). These functions are recognized as interrelated fundamental cognitive processes (Ku, 2018) and share similar underlying neural mechanisms. In sports, the effectiveness of attentional resource transitions often plays a critical role in competitive sports, and elite athletes appear to be able to operate efficiently in the transition of information processing (Eccles, 2006; Ericsson, 2006; Furley P. and Memmert, 2010), allowing motor skills to be performed appropriately. A meta-analysis of studies of athletes of different skill levels revealed that athletes with higher skill levels performed better cognitive skills than athletes with lower skill levels (Tomporowski and Pesce, 2019), however, the elements of cognitive skills in the higher skills athletes have not yet clear (Kalén et al., 2021).

The WM model not only facilitates information storage but also integrates cognitive control and attention mechanisms (Baddeley, 1992; Baddeley, 2003), allowing the model to incorporate complex behaviors and their underlying processes. Athletes' performance is influenced by their WM capacity when engaging in two attention-demanding tasks when executing a motor action while processing external stimuli. Other studies have demonstrated a reciprocal relationship between attention and WM (Furley P. A. and Memmert, 2010; Furley and Wood, 2016).

Attention encompasses all cognitive processes and regulates the activation of internal and external representations (Posner and Petersen, 1990; Knudsen, 2007). This regulation could allow the outsources of stimuli to enter the WM (Atkinson and Shiffrin, 1968), and WM influences attentional control (Soto and Humphreys, 2007). In this way, higher WM capacity can be preserved as active memory. Therefore, WM plays a crucial role in the comprehension of human cognition in real-life contexts. Empirical studies on athletes support the role of WM in decision-making, which relies on controlled attention (Furley and Memmert, 2012). Furley and Memmert (2013) provided evidence that WM plays a crucial role in directing and allocating attention in athletes. In addition, the WM capacity indicates an individual's ability to control attention across domains (Kane et al., 2007).

WM is a cognitive system comprising multiple elements. This system incorporates the executive in the center, along with two subsidiary mechanisms: the phonological loop and the visuospatial sketchpad (Baddeley and Hitch, 1974; Baddeley, 1992; Baddeley, 2003; Baddeley, 2007). They argued that WM not only accurately predicts a person's ability to control their attention but also those who may falter in high stress during the games (Furley and Memmert, 2012). Conversely, those with low WM struggled to adapt their strategies to meet the game's demands, and those who scored high on WM evaluations displayed a heightened ability to concentrate. Supported by empirical studies on athletes, WM capacity plays a role in decision-making in tactical games, which depends on controlled attention (Furley and Memmert, 2012). Some researchers have argued that sports experts do not achieve higher WM scores (Furley and Wood, 2016; Buszard and Masters, 2018). However, researchers have not differentiated their findings across expertise (Swann et al., 2015).

In the context of performance, the computer-based findings of Furley and Memmert (2012) suggest that WM can predict the ability to resolve response competitions. Athletes' performance prediction may be related to their better selective attention (Abernethy, 1988; Schumacher et al., 2018), focusing on crucial information and performing cognitive processing in a complex environment (Johnston and Dark, 1986). However, some studies have demonstrated that basketball players perform the same cognitive skills as nonathletes (Furley P. and Memmert, 2010); further research should clarify these mechanisms.

Regarding the maturation of athletes' age of development, studies indicated that age affects the reaction time (RT) in the different age groups. According to Petrakis (1985), 10-year-old players achieved faster detection time compared to 8-year-olds. Benguigui and Ripoll (1998) stated that age affects the timing of the initiation of the response, and RT decreases as age increases into adulthood. Williams et al. (2002) examined youth tennis players at different age levels and showed that the younger age groups performed slower response initiation times than the older groups. On the other hand, when consider gender effect in RT, research indicates that between the ages of 4 and 9, hormonal differences lead to boys having faster detection times than girls (Petrakis, 1985). This advantage continues into adulthood, with males consistently outperforming females in detection tasks (Brady, 1996; Caccese et al., 2020). As mentioned above, both age and gender significantly influence RT.

From the perspective of working memory, considering the effects of gender and age, Tremblay et al. (2022) found significant differences among youth athletes in terms of body measurement, elite levels, and perceptual and cognitive skills. Ward and Williams (2003) found that in terms of cognitive skills related to working memory, age was a more reliable predictor of structured memory recall than motor ability. Similarly, Farrell Pagulayan et al. (2006) identified significant differences based on grade, reinforcing the influence of age on memory performance. Neuroscientific research indicates gender differences in WM, which are seen in the activation patterns: females predominantly activate the limbic and prefrontal areas in contrast to males, who demonstrate a more dispersed activation pattern, notably in the parietal areas (Hill et al., 2014). Considering gender in growth and development, the rapid growth stage of height in females is at 11 years of age, and after 16 years of age, height development enters the end stage, it can be seen that the growth and maturation of female in adolescent, female athletes is faster than that of male athletes in the adolescent stage (Goodway et al., 2021). Nevertheless, the research of WM in adolescents found no significant gender differences (Farrell Pagulayan et al., 2006; Rigoli et al., 2012); Research by Rigoli et al. (2012) examining motor coordination, academic achievement, and working memory (WM) found no gender differences among adolescent participants. Similarly, Farrell Pagulayan et al. (2006) reported no significant gender effects in their study. Moreover, studies have indicated that adult males respond more quickly to WM tasks, with no observed differences in accuracy between the gender (Loring-Meier and Halpern, 1999).

As previously stated, studies investigating RT and WM in badminton athletes have revealed that various factors, including age, gender, influence the perceptual-cognitive skills (Brady, 1996; Loring-Meier and Halpern, 1999; Farrell Pagulayan et al., 2006; Caccese et al., 2020). Furthermore, only a few articles have assessed cognitive skills in childhood and adolescence to identify their role in the field of sports (Ward and Williams, 2003; Ishihara et al., 2019; Murr et al., 2021) and future sporting success (Kalén et al., 2021). Further studies should incorporate controls for age-difference groups with high fitness levels to enable meaningful comparisons (Hillman et al., 2008, 2015).

To the best of our knowledge, no previous research has investigated the perceptual-cognitive skills of experienced badminton players with regard to gender, age and elite levels among student-athletes. Therefore, this study aimed to examine the effects of age and gender in adolescent badminton players on perceptual and cognitive skills in RT and WM. Additionally, we explored whether elite levels could be influenced by perceptual and cognitive skills.

Based on our findings, we hypothesized that age and gender impact perceptual-cognitive skills in adolescent, and that badminton athletes with greater perceptual and cognitive skills exhibit better elite levels.

2 Materials and methods

2.1 Participants

A total of 57 adolescent badminton athletes were recruited. The participants were divided into two main groups based on academic levels, reflecting their developmental stages (males rapid growth in 16–18 years with senior high stage, females rapid growth in 13–16 years with junior high stage), with consideration for gender-specific growth patterns. In Taiwan, this approach extends to badminton competition and promotes fairness by acknowledging these differences. The junior high school group consisted of adolescent athletes who averaged 13.36 ± 1.14 years in age, with 22 females and 11 males, while senior high school group averaging 16.5 ± 0.84 years in age comprised 11 females and 13 males. This study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of the University of Taipei (protocol code: UT-IRB No. IRB-2020-073, February 9, 2021–2024) and received written informed consent from the participants' legal guardians.

2.2 Procedures

All participants were tested in a laboratory and the experiment lasted for approximately 40 min. Prior to the test session, the participants were required to complete a questionnaire. Badminton players answer these questions to obtain scores, which are then used the formula by Swann et al. (2015) to calculate their competitive scores. All participants responded on a 1,428.4 × 803.5 mm and 8 ms display to acquire reaction times. The testing methods for spatial priming and WM capacity are described as the cognitive component test section.

2.2.1 Classify the athlete's elite levels

In this questionnaire, they were asked to rate their sport performance based on their career competition results and using the classification developed by Swann et al. (2015) for adolescent players, in which competitive scores were calculated as per the existing literature. The competitive scores of adolescent athletes are judged based on researcher questions developed by Swann et al. (2015), which consist of two parts: competition within the athlete's country and competition within the sport globally. In a country, an elite athlete's status is determined by the level of competition within their sport, depending on factors such as the country's size and the sport's popularity. Similarly, global competition in the sport determines an athlete's status, considering the number of competitors worldwide and the effort required to excel. The resulting scores were subsequently classified as follows: 1–4 = Semi-Elite athletes, 4–8 = Competitive Elite athletes, 8–12 = Successful Elite athletes, and 12–16 = World-Class Elite athletes. Table 1 contains the elite levels and scores of the participants. The higher level of the elite, the higher the score the athlete received.

2.2.2 Cognitive component test

2.2.2.1 Spatial priming task: reaction time

SPT evaluates rapid attention and response switching in a changing signal. The experimental procedure was a SPT from a The Psychology Experiment Building Language (PEBL) test battery

TABLE 1 Elite levels scores of age and gender badminton players.

Age/academic phase	Gender	*N*	Age	Training years	Elite athlete's levels (Swann et al., 2015)				
					Semi elite	Competitive elite	Successful elite	World class elite	Scores
Junior	Female players	22	13.64 ± 1.13	6.29	15	7	1	0	3.67
	Male players	11	12.82 ± 0.98	4.27	8	3	0	0	4.32
Senior	Female players	11	16.73 ± 0.90	8.77	1	10	5	0	5.75
	Male players	13	15.85 ± 0.55	8.84	5	8	1	0	5.05

Elite athlete's levels score, semi elite 1–4, competitive elite 4–8, successful elite 8–12, world class elite 12–16.

(Mueller and Piper, 2014). Correlations have been observed between RT and perceptual speed (Carlson et al., 1983); thus, we used a SPT of RT to test athletes' attention ability. In this program, the participants were presented with a 3 × 3 array of squares on a screen. Whenever the program was executed, it ran a total of 54 trials, according to Nelson (2013) PEBL technical report 2013-1, there are significant difference between five conditions. During each trial, the participants were instructed to respond with both speed and precision when one of the nine squares turned blue (target square). Before the target square appeared, one of the squares briefly flashed yellow (visual cue). The cue was not always in the same location as the target square, and the SPT measurement variables were as follows: in some trials, there was no cue (NC), the cue appeared in the same row (SR), the cue appeared in the same column (SC), the cue appeared in the same square (SS), and the cue appeared in a different row and column (OS). A total of 54 trials were conducted each time the program was conducted. Thus, we can compare the cueing conditions with research conducted using this task in other subjects, specifically in different sports.

2.2.2.2 Working-memory: capacity of Corsi block-tapping

Widespread usage in cognitive psychology is found in the operation, counting, and reading span tasks (Conway et al., 2005). Counting span tasks to assess working memory. These tasks typically require multiple subcomponents of executive functions (Diamond, 2013). In the present study, the Corsi block-tapping task (CCT) served as a measure of spatial ability. This task demonstrates the sensitivity of the dependent measure, which has been previously employed to assess developmental differences among children and adolescents (Farrell Pagulayan et al., 2006), Additionally, it has been applied in the field of sports (Furley P. and Memmert, 2010). To assess WM capacity, we used the Spatial Working Memory (SWM) task, a computerized version of the CCT. The participants reproduced the color-changing sequences by touching the corresponding boxes on the screen. The task began with a two-box sequence and advanced to nine boxes. The outcome measure is the span length, which indicates WM capacity. The (CCT) includes variables such as Block Span (BS), Total Score (TS), Total Correct Trials (TC), and Memory Span (MS).

2.3 Statistical analysis

We used a two-way MANOVA for measures, with gender and age as independent variables and within the SPT task as dependent variables. Wilks' lambda values for group differences in a set of dependent variables were determined (Tabachnick et al., 2013). Similarly, a two-way MANOVA was used for the task of the CCT, and we examined the main effects and interactions of both gender and age. Effect sizes were expressed as partial eta-squared values in MANOVA (small ≥0.01, medium ≥0.06, large ≥0.14), with Cohen's d (small ≥0.2, medium ≥0.5, large ≥0.8) indicating mean group differences. Significance was set at 0.05 (Cohen, 2013). The groups of elite levels were divided into semi-elite and competitive-elite categories, with age serving as a significant factor. Therefore, the MANCOVAs were employed to analyze the association between WM and the same statistical method was used for spatial priming tasks. Based on the classification devised by Swann et al. (2015), the elite levels of youth athletes was divided into two groups: semi-elite and competitive-elite. SPSS Statistics software (version 26) was used to analyze the data, and the significance level was set at $p < 0.05$.

3 Result

The normality of the distribution of continuous variables was assessed using the Kolmogorov–Smirnov (K–S) Normality Test, which revealed that the SPT outcomes did not significantly deviate from a normal distribution ($p > 0.05$). In the CCT, the normality of the distribution was rejected ($p < 0.05$). so a generalized rank-order method for nonparametric two-way MANOVA testing of CCT data was used (Thomas et al., 1999). Reliability of within-subject variation in SPT typical error is 58.32 (10%); CCT typical error is 1.024 (14%) (Hopkins, 2000).

In the SPT task, the MANOVA revealed no significant main effect for the SPT of gender, with Wilks' lambda = 0.872, F (5, 49) = 1.432, $p = 0.22$, $\eta^2 = 0.128$ and Observed power = 0.46; male and female players revealed the same RT. Consequently, the significant main effect of age was observed with Wilks' lambda = 0.800, F (5, 49) = 2.445, $p = 0.047$, $\eta^2 = 0.20$, and Observed power = 0.72, indicating that senior high badminton players revealed faster RT than junior high players did. There was no significant interaction between gender and age group with Wilks' lambda = 0.836, F (5, 49) = 1.927, $p = 0.107$, $\eta^2 = 0.164$, and Observed power = 0.60. Group performance of SPT is shown in Table 2 and Figure 1. In the CCT task, there are no significant main effect in non-parametric MANOVA tested in gender, Wilks' lambda = 0.977, F (3, 51) = 0.394, $p = 0.758$, $\eta^2 = 0.02$, Observed power = 0.12, Male and Female players revealed the same span of CCT task, subsequently, age effect in Wilks' lambda = 0.756, F (3, 51) = 5.489, $p = 0.002$, $\eta^2 = 0.244$, Observed power = 0.92, senior high badminton player revealed longer CCT Span than junior high players, and no interaction between gender and age factors, Wilks' lambda = 0.990, F (3, 51) = 0.177, $p = 0.911$, $\eta^2 = 0.010$, Observed power = 0.81, respectively, groups performance of CCT are shown in Table 3 and Figure 2. Given the age effect observed in task performance, we included age as a covariance, with semi-elite and competitive-elite youth athletes as fixed variables in the SPT and CCT. The result indicated that for the SPT there was no significant difference in the performance of SPT when comparing semi-elite to competitive-elite youth athletes, with Wilks' lambda = 0.954, F (5, 51) = 0.490, $p = 0.782$, $\eta^2 = 0.046$, and Observed power = 0.15; competitive-elite and semi-elite players revealed the same RT in SPT. In the CCT, semi-elite and competitive-elite revealed a significant effect on performance, with Wilks' lambda = 0.847, F (3, 53) = 3.137, $p = 0.03$, $\eta^2 = 0.153$, Observed power = 0.69; competitive-elite players revealed longer span of CCT than semi-elite players. The elite levels of the youth athletes is illustrated in Table 1. MANCOVA was used to analyze the effects of WM in semi-elite and competitive-elite youth athletes, and the same statistical method was employed for the spatial priming task.

4 Discussion

This study primarily aimed to examine whether there are differences in perceptual-cognitive skills in terms of WM and SPT-RTs among adolescent badminton athletes based on age and gender. We also analyzed the effect between perceptual-cognitive skills and

TABLE 2 Age and gender, perceptual and cognitive skills performance in adolescent badminton athletes.

MANOVA		Age*		Gender	
Measure		Junior = 33	Senior = 24	Female = 33	Male = 24
Spatial-Prime (ms)	NC	574.11 ± 72	542.81 ± 59	558.28 ± 68	564.57 ± 71
	SR	520.45 ± 60	490.77 ± 39	497.95 ± 42	521.70 ± 65
	SC	539.16 ± 74	494.73 ± 55	520.68 ± 75	520.14 ± 64
	SS	505.64 ± 44	501.63 ± 44	503.48 ± 42	504.60 ± 46
	OS	530.45 ± 48	508.60 ± 59	518.26 ± 48	525.36 ± 62
Corsi-Block (Score)	BS	6.76 ± 1.2	7.58 ± 0.8	7.12 ± 1.2	7.08 ± 1.01
	TS	62.61 ± 21.47	79.33 ± 15.4	69.88 ± 24.1	69.33 ± 15.0
	TC	9.15 ± 1.62	10.38 ± 1.2	9.64 ± 1.8	9.71 ± 1.04
	MS	5.57 ± 0.8	6.18 ± 0.6	5.81 ± 0.9	5.85 ± 0.5

Spatial-Prime (ms): NC, trials was no cue; SR, cue appear in the same row; SC, cue appear in the same column; SS, cue appear in the same square; OS, cue appear in a different row.
Corsi-Block (Score): BS, block span; TS, total score; TC, total correct trails; MS, memory span.
*$p < 0.05$.

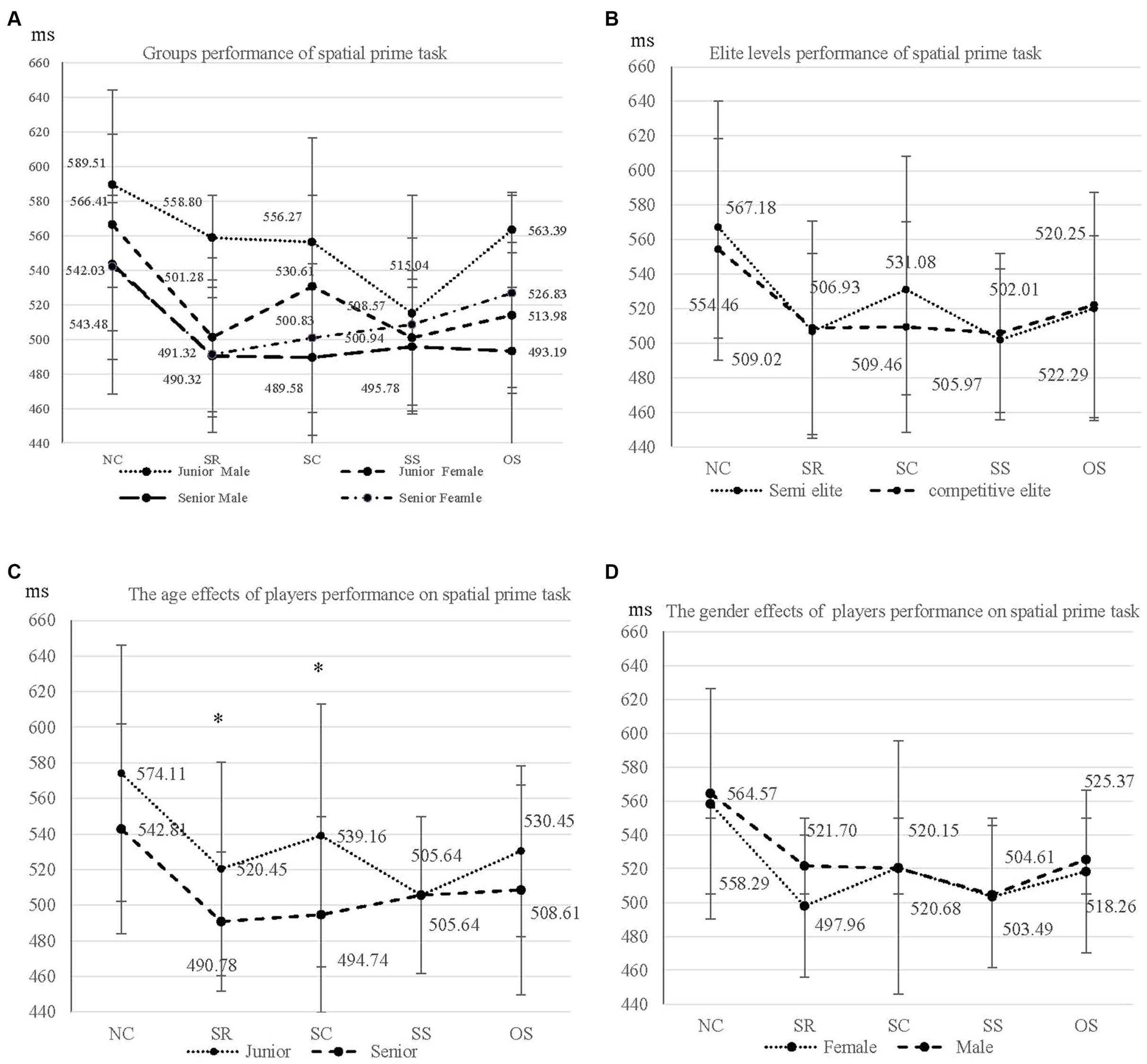

FIGURE 1
Badminton player of groups and gender differences spatial prime task performances. NC, trials was no cue; SR, cue appear in the same row; SC, cue appear in the same column; SS, cue appear in the same square; OS, cue appear in a different row. * $p < 0.05$.

TABLE 3 Sports performance, and perceptual and cognitive skills in adolescent badminton athletes.

MANCOVA		Elite level	
Measure		Semi-elite = 29	Competitive-elite = 28
Spatial-prime (ms)	NC	567.18 ± 73	554.46 ± 64
	SR	506.93 ± 45	509.01 ± 62
	SC	531.08 ± 77	509.45 ± 61
	SS	502.01 ± 41	505.96 ± 46
	OS	520.25 ± 42	522.28 ± 65
MANCOVA		Elite level *	
Corsi-Block (Score)	BS *	6.55 ± 1.21	7.68 ± 0.81
	TS	61.79 ± 22.21	77.79 ± 15.68
	TC	9.21 ± 1.69	10.14 ± 1.29
	MS	5. 60 ± 0.87	6.07 ± 0.64

Spatial-Prime (ms): NC, trials was no cue; SR, cue appear in the same row; SC, cue appear in the same column; SS, cue appear in the same square; OS, cue appear in a different row. Corsi-Block (Score): BS, block span; TS, total score; TC, total correct trails; MS, memory span.
*$p < 0.05$.

elite levels at the semi-elite and competitive-elite levels in badminton adolescent athletes. The discussions are as follows.

4.1 Perceptual-cognitive skills of SPT-RT

In our results of SPT, no gender effect was observed in the groups of female and male badminton players; however, age had a significant effect on the senior and junior high groups, as senior players exhibited better performance in terms of RT than junior high players did. From the perspective of maturation (Goodway et al., 2021), the age maturation affects players' RTs, and research has shown that age affects the timing of response initiation in sports, with older age groups exhibiting less RT than younger age groups. Söğüt and Koçak (2009) indicated that older child players (10 years old) had significantly higher scores in detection time than those of 8-year-olds. Benguigui and Ripoll (1998) show that age affects the timing of detection and has an inverse correlation. In line with previous research, our results showed that senior players, owing to their developmental maturity, exhibited better RT than junior players during adolescence. The RT decreases as age increases into adulthood (Petrakis, 1985; Williams and Ericsson, 2005). The results of the SPT of five cueing conditions revealed a similar trend to that observed by Nelson (2013). The slowest RT was observed in the NC condition (800 ms), followed by the SC condition (750 ms). The results indicated that senior high school athletes exhibited significantly faster reaction times than junior high school athletes in both the SR (490 ms) and SC (494 ms) conditions. Additionally, the CCT task resulted in a higher memory span in senior athletes than in junior athletes. The results presented here are in accordance with the findings of Furley and Memmert (2013), which indicate that WM capacity is a crucial role of an individual's capacity to control attention and to operate efficiently in the transition of information processing (Eccles, 2006; Ericsson, 2006; Furley P. and Memmert, 2010).

In terms of gender differences, our results showed no gender effect in badminton players when performing SPT-RT, even though female athletes mature faster than their male counterparts during adolescence (Goodway et al., 2021). Additionally, with the introduction of hormones until the age of 4–9 years, boys could be more successful than girls in terms of detection time (Petrakis, 1985). This trend continues into adulthood, as males consistently outperform females (Brady, 1996; Caccese et al., 2020). However, our results revealed that both males and females performed equally well in the RT task, regardless of gender. From the perspective of training, deliberation in practice could reduce gender differences in the ability of cognitive (Chance and Goldstein, 1971; Connor et al., 1977), specifically the detection time decreases and have better ability to select RT through badminton training (Liu et al., 2017). Furthermore, experienced athletes have better perceived time than novice athletes (Phomsoupha and Laffaye, 2015).

4.2 Perceptual-cognitive skills of WM Corsi-block span

In the CCT result, no gender effect was observed among the groups of female and male adolescent badminton players; however, significant differences were found based on age between the junior and senior high groups, indicating that age affected adolescent badminton players, and senior players performed better than junior badminton players, this finding is consistent with the study by Ward and Williams (2003) in which age was a stronger predictor of structured memory recall than ability. Regarding the development and gender-based research in WM, our findings correspond with the research of Farrell Pagulayan et al. (2006) result, as their study also found no gender effect but it did identify significant differences based on grade. Consistent with the results of Rigoli et al. (2012), research investigating motor coordination, academic achievement, and WM also showed no gender effects in adolescent participants. Elite players blend contextual information with stored memory in a way that differs systematically from their sub-elite peers (Ward and Williams, 2003).

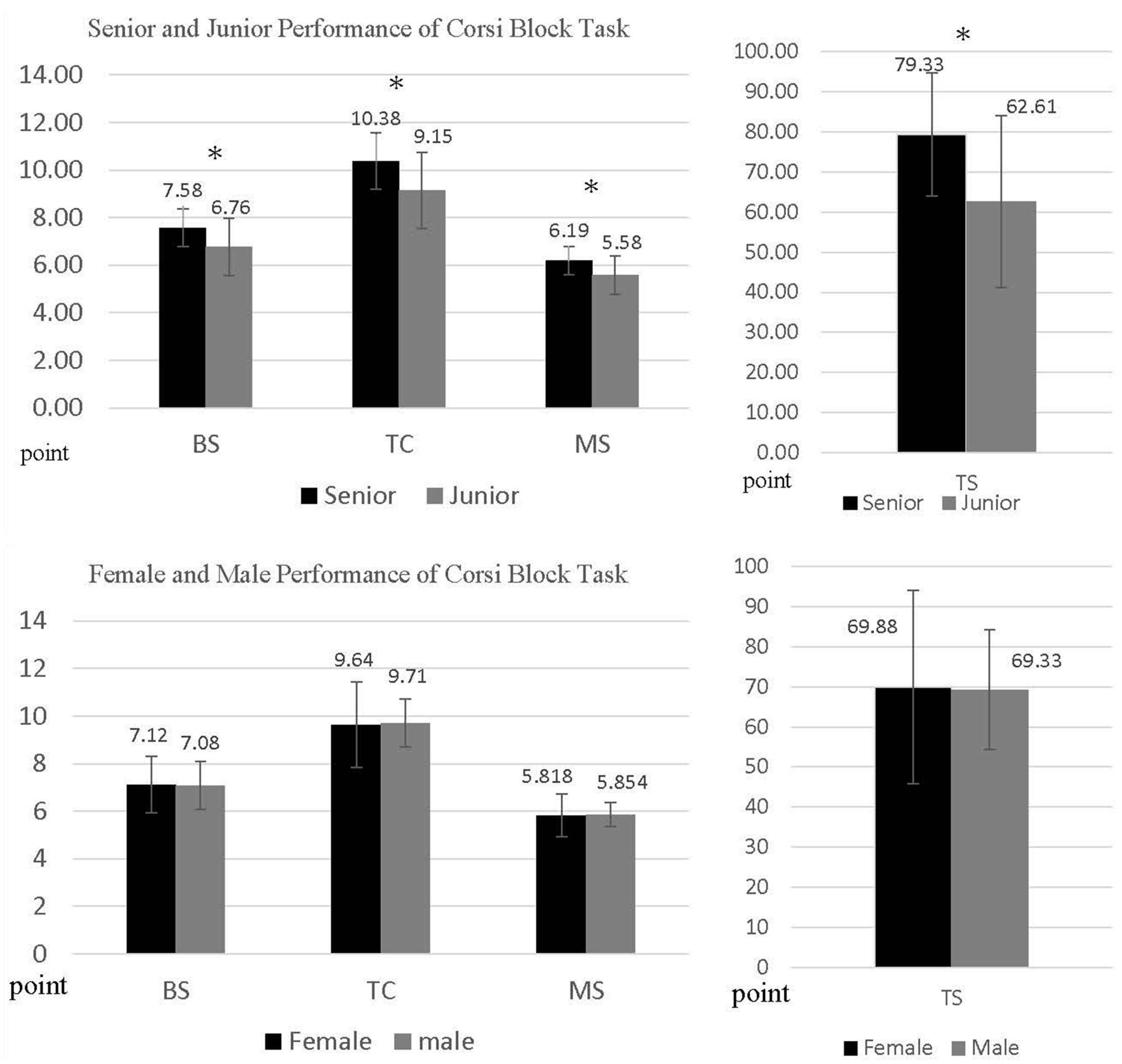

FIGURE 2
Badminton player of groups and gender differences Corsi block task performances. BS, block span; TS, total score; TC, total correct trails; MS, memory span. * $p < 0.05$.

4.3 Elite levels level and perceptual-cognitive level

In this study, we assessed the elite levels of adolescent badminton players using Swann et al. (2015) equation to classify athletes into semi-elite and competitive-elite players and analyzed the association between elite levels and perceptual-cognitive skills. The results revealed that in the SPT task, there was no difference in RT performance, which means that the selection RT was the same between semi-elite and competitive-elite players; however, regarding the WM in the CCT, competitive-elite players showed better results than semi-elite players (see Table 3; Figure 3). These findings are consistent with the Alves et al. (2013) studies and the same with athletes with higher skills performed better cognitively than athletes with lower skills (Ward and Williams, 2003; Tomporowski and Pesce, 2019), Elite athletes possess superior cognitive skills and support the concept of WM as executive attention (Engle, 2002), the viewpoint suggesting that WM capacity is linked to controlled attention and implying that WM capacity does not directly represent a person's ability to keep items in their short-term memory. Instead, it symbolizes a person's capacity to persist with task objectives, minimize disturbances, and avoid distractions (Engle, 2002). Furley and Memmert (2012) indicated that individuals with higher WM capabilities were notably better at maintaining focus and resisting interruptions during sports, underscoring the critical importance of WM in managing attention during athletic competitions. Additionally, Furley and Memmert (2013) illustrated how athletes' WM content is instrumental in shifting their attentional focus, enabling them to consciously direct their attention toward achieving targeted behaviors. Further evidence points to a two-way interaction between the contents of attention and WM; attention is a gateway for stimuli to enter WM (Atkinson and Shiffrin, 1968), while researchers have found that the contents of WM can also shape attentional control (Soto and Humphreys, 2007; Soto and Humphreys, 2008). Thus, competitive

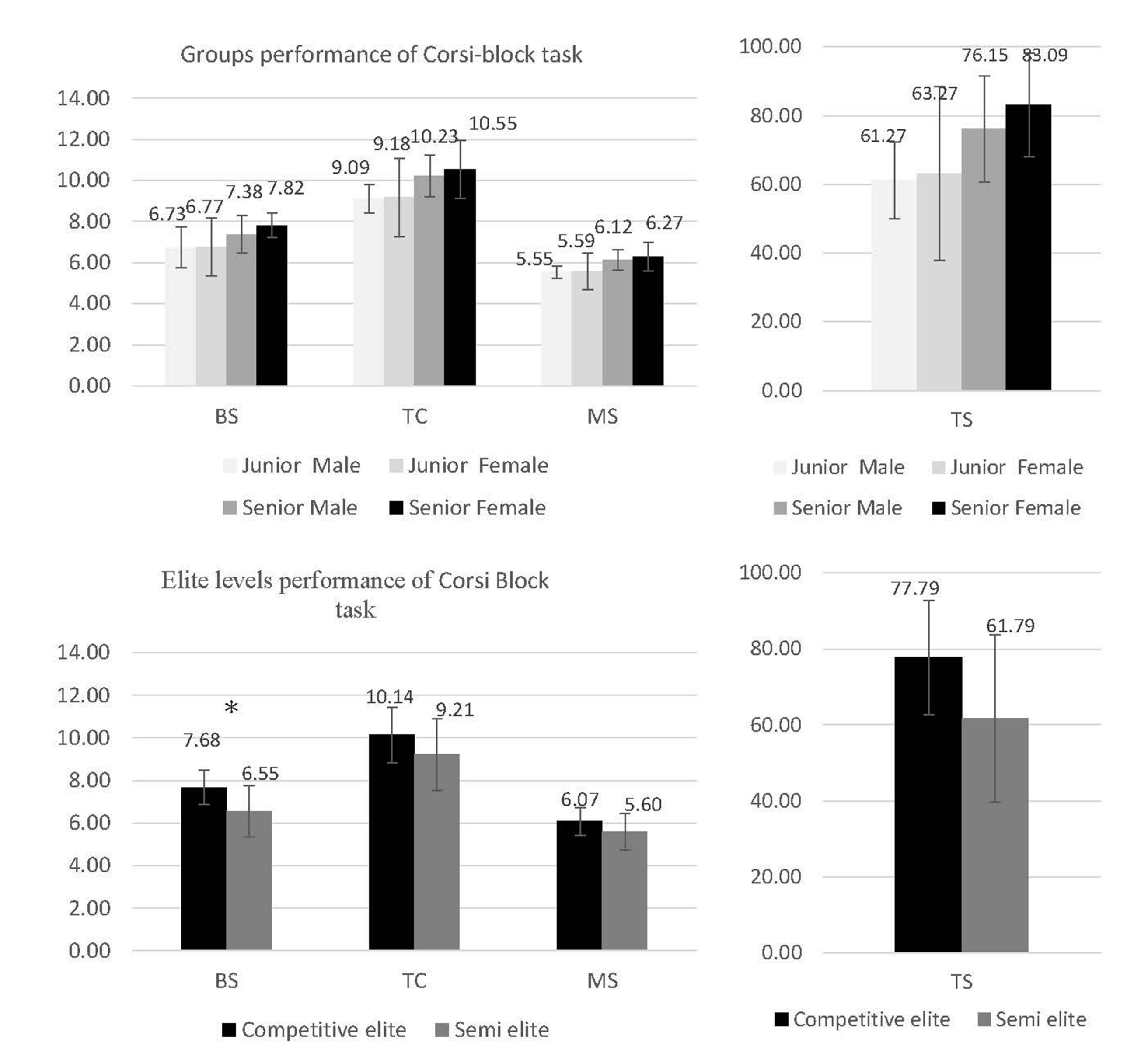

FIGURE 3
Badminton player of elite levels Corsi block task performances. Semi elites $n = 29$, competitive elites $n = 28$ (including 2 successful elites). We combine the competitive elite athletes and successful elites. * $p < 0.05$.

athletes seem well in attention to perform well in open-skill badminton sports. From childhood through adolescence to adulthood, the greater the WM, the greater the motor processing in the development effect (Rigoli et al., 2012; Alves et al., 2013; Lehmann et al., 2014), which further indicates that higher elite levels of competitive-elite badminton players' WM is better than lower elite levels of semi-elite adolescent players. WM capacity difference affects competition responses; higher WM capacity has more proficiency in adjusting tactical decisions, while lower WM capacity may fails to adjust tactical decisions to the demands of the game.

5 Limitations

The scope of this study was limited to adolescent badminton athletes; therefore, the results cannot be generalized to other sports or age groups. Additionally, the study only examined cognitive abilities related to WM and SPT-RTs. The cognitive tasks used in this study did not cover all the cognitive parameters, such as cognitive flexibility and inhibition ability, which are typically included in cognitive studies. Hence, it is crucial for future studies to incorporate more comprehensive cognitive tests to assess different aspects of cognition. Moreover, the study did not gather data on the transition from adolescence to college age, potentially affecting the outcomes of the variables.

6 Conclusion

In the current study, we examined the perceptual-cognitive skills of SPT-RTs and CCT-WM across gender, age and elite levels among badminton adolescent athletes. The results indicated that age affects the perceptual-cognitive skills of adolescent players. Senior high school players exhibited better perceptual-cognitive abilities than junior high school players did. No gender effects were found in the perceptual skills of the adolescents, and the age effect was consistent across genders. Regarding the different levels of elite in adolescent badminton players, SPT-RTs were similar in the semi-elite and competitive players; however, regarding the WM in CCT, competitive elite players outperformed semi-elite players. Our results show that the WM plays a crucial role in open skills in elite levels specific to badminton. There were no gender effects; only the age difference effect among adolescent badminton players was observed. Female and male adolescents of the same age perform equally well in terms of perceptual-cognitive skills in the same age. When developing advanced skills for elite levels, perceptual-cognitive skills should be considered during routine training. Future studies should focus on the potential of perceptual-cognitive expertise in sports to assist trainers in developing expert athletes and gain insight into the brain structure and functional maturation that differs between individuals with varying levels of sports experience and expertise, ultimately enhancing higher levels.

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

This study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of the University of Taipei (protocol code: UT-IRB No. IRB-2020-073, February 9, 2021–2024) and received written informed consent from the participants' legal guardians. 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 minor(s)' legal guardian/next of kin for the publication of any potentially identifiable images or data included in this article.

Author contributions

K-CW: Writing – original draft, Writing – review & editing. Y-LL: Data curation, Writing – original draft. S-CC: Writing – review & editing.

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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.

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References

Abernethy, B. (1988). Visual search in sport and ergonomics: its relationship to selective attention and performer expertise. *Hum. Perform.* 1, 205–235. doi: 10.1207/s15327043hup0104_1

Alves, H., Voss, M. W., Boot, W. R., Deslandes, A., Cossich, V., Salles, J. I., et al. (2013). Perceptual-cognitive expertise in elite volleyball players. *Front. Psychol.* 4:36. doi: 10.3389/fpsyg.2013.00036

Atkinson, R. C., and Shiffrin, R. M. (1968). "Human memory: a proposed system and its control processes", in *Psychology of Learning and Motivation: Advances in Research and Theory*. eds. K. W. Spence and J. T. Spence (New York: Academic). 89–195.

Baddeley, A. (1992). Working memory. *Science* 255, 556–559. doi: 10.1126/science.1736359

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nat. Rev. Neurosci.* 4, 829–839. doi: 10.1038/nrn1201

Baddeley, A. (2007). Working memory, thought, and action. Oxford: Oxford University Press.

Baddeley, A. D., and Hitch, G. (1974). "Working memory" in *The Psychology of learning and motivation. Advances in research and theory*. ed. G. H. Bower (New York: Academic Press). 47–89.

Benguigui, N., and Ripoll, H. (1998). Effects of tennis practice on the coincidence timing accuracy of adults and children. *Res. Q. Exerc. Sport* 69, 217–223. doi: 10.1080/02701367.1998.10607688

Brady, F. (1996). Anticipation of coincidence, gender, and sports classification. *Percept. Mot. Skills* 82, 227–239. doi: 10.2466/pms.1996.82.1.227

Buszard, T., and Masters, R. S. (2018). Adapting, correcting and sequencing movements: does working-memory capacity play a role? *Int. Rev. Sport Exerc. Psychol.* 11, 258–278. doi: 10.1080/1750984X.2017.1323940

Caccese, J. B., Eckner, J. T., Franco-Mackendrick, L., Hazzard, J. B., Ni, M., Broglio, S. P., et al. (2020). Clinical reaction-time performance factors in healthy collegiate athletes. *J. Athl. Train.* 55, 601–607. doi: 10.4085/1062-6050-164-19

Carlson, J. S., Jensen, C. M., and Widaman, K. F. (1983). Reaction time, intelligence, and attention. *Intelligence* 7, 329–344. doi: 10.1016/0160-2896(83)90008-9

Chance, J. E., and Goldstein, A. G. (1971). Internal-external control of reinforcement and embedded-figures performance. *Percept. Psychophys.* 9, 33–34. doi: 10.3758/BF03213024

Cohen, J. (2013). Statistical power analysis for the behavioral sciences. New York: Routledge, Academic Press.

Connor, J. M., Serbin, L. A., and Schackman, M. (1977). Sex differences in children's response to training on a visual-spatial test. *Dev. Psychol.* 13, 293–294. doi: 10.1037/0012-1649.13.3.293

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

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

Eccles, D. W. (2006). Thinking outside of the box: the role of environmental adaptation in the acquisition of skilled and expert performance. *J. Sports Sci.* 24, 1103–1114. doi: 10.1080/02640410500432854

Engle, R. W. (2002). Working memory capacity as executive attention. *Curr. Dir. Psychol. Sci.* 11, 19–23. doi: 10.1111/1467-8721.00160

Ericsson, K. A. (2006). The Cambridge handbook of expertise and expert performance. Cambridge: Cambridge University Press.

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

Furley, P., and Memmert, D. (2010). Differences in spatial working memory as a function of team sports expertise: the Corsi block-tapping task in sport psychological assessment. *Percept. Mot. Skills* 110, 801–808. doi: 10.2466/pms.110.3.801-808

Furley, P. A., and Memmert, D. (2010). The role of working memory in sport. *Int. Rev. Sport Exerc. Psychol.* 3, 171–194. doi: 10.1080/1750984X.2010.526238

Furley, P. A., and Memmert, D. (2012). Working memory capacity as controlled attention in tactical decision making. *J. Sport Exerc. Psychol.* 34, 322–344. doi: 10.1123/jsep.34.3.322

Furley, P., and Memmert, D. (2013). "Whom should I pass to?" the more options the more attentional guidance from working memory. *PLoS One* 8:e62278. doi: 10.1371/journal.pone.0062278

Furley, S., 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

Goodway, J. D., Ozmun, J. C., and Gallahue, D. L. (2021). Understanding motor development: infants, children, adolescents, adults. Burlington: Jones & Bartlett Learning.

Hill, A. C., Laird, A. R., and Robinson, J. L. (2014). Gender differences in working memory networks: a BrainMap meta-analysis. *Biol. Psychol.* 102, 18–29. doi: 10.1016/j.biopsycho.2014.06.008

Hillman, C. H., Erickson, K. I., and Kramer, A. F. (2008). Be smart, exercise your heart: exercise effects on brain and cognition. *Nat. Rev. Neurosci.* 9, 58–65. doi: 10.1038/nrn2298

Hillman, C. H., Khan, N. A., and Kao, S.-C. (2015). The relationship of health behaviors to childhood cognition and brain health. *Ann. Nutr. Metab.* 66, 1–4. doi: 10.1159/000381237

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Med.* 30, 1–15. doi: 10.2165/00007256-200030010-00001

Hung, C.-L., Tseng, J.-W., Chao, H.-H., Hung, T.-M., and Wang, H.-S. (2018). Effect of acute exercise mode on serum brain-derived neurotrophic factor (Bdnf) and task switching performance. *J. Clin. Med.* 7:301. doi: 10.3390/jcm7100301

Ishihara, T., Kuroda, Y., and Mizuno, M. (2019). Competitive achievement may be predicted by executive functions in junior tennis players: an 18-month follow-up study. *J. Sports Sci.* 37, 755–761. doi: 10.1080/02640414.2018.1524738

Jin, H., Xu, G., Zhang, J. X., Gao, H., Ye, Z., Wang, P., et al. (2011). Event-related potential effects of superior action anticipation in professional badminton players. *Neurosci. Lett.* 492, 139–144. doi: 10.1016/j.neulet.2011.01.074

Johnston, W. A., and Dark, V. J. (1986). Selective attention. *Annu. Rev. Psychol.* 37, 43–75. doi: 10.1146/annurev.ps.37.020186.000355

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

Kane, M. J., Bleckley, M. K., Conway, A. R., and Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *J. Exp. Psychol. Gen.* 130, 169–183. doi: 10.1037/0096-3445.130.2.169

Kane, M. J., Conway, A. R., Hambrick, D. Z., and Engle, R. W. (2007). Variation in working memory capacity as variation in executive attention and control. *Var. Work. Mem.* 1, 21–48. doi: 10.1093/acprof:oso/9780195168648.003.0002

Kane, M. J., and Engle, R. W. (2003). Working-memory capacity and the control of attention: the contributions of goal neglect, response competition, and task set to Stroop interference. *J. Exp. Psychol. Gen.* 132, 47–70. doi: 10.1037/0096-3445.132.1.47

Knudsen, E. I. (2007). Fundamental components of attention. *Annu. Rev. Neurosci.* 30, 57–78. doi: 10.1146/annurev.neuro.30.051606.094256

Ku, Y. (2018). Selective attention on representations in working memory: cognitive and neural mechanisms. *PeerJ* 6:e4585. doi: 10.7717/peerj.4585

Lehmann, J., Quaiser-Pohl, C., and Jansen, P. (2014). Correlation of motor skill, mental rotation, and working memory in 3- to 6-year-old children. *Eur. J. Dev. Psychol.* 11, 560–573. doi: 10.1080/17405629.2014.888995

Liu, T., Shao, M., Yin, D., Li, Y., Yang, N., Yin, R., et al. (2017). The effect of badminton training on the ability of same-domain action anticipation for adult novices: evidence from behavior and erps. *Neurosci. Lett.* 660, 6–11. doi: 10.1016/j.neulet.2017.08.038

Loring-Meier, S., and Halpern, D. F. (1999). Sex differences in visuospatial working memory: components of cognitive processing. *Psychon. Bull. Rev.* 6, 464–471. doi: 10.3758/BF03210836

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

Mori, S., Ohtani, Y., and Imanaka, K. (2002). Reaction times and anticipatory skills of karate athletes. *Hum. Mov. Sci.* 21, 213–230. doi: 10.1016/S0167-9457(02)00103-3

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

Murr, D., Larkin, P., and Höner, O. (2021). Decision-making skills of high-performance youth soccer players: validating a video-based diagnostic instrument with a soccer-specific motor response. *Ger. J. Exerc. Sport Res.* 51, 102–111. doi: 10.1007/s12662-020-00687-2

Nelson, B. (2013). The effects of attentional cuing and input methods on reaction time in human-computer interaction, *Pebl technical report*, 2013–01. Michigan: Michigan Technological University.

Petrakis, E. (1985). Sex differences and specificity of anticipation of coincidence. *Percept. Mot. Skills* 61, 1135–1138. doi: 10.2466/pms.1985.61.3f.1135

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

Posner, M. I., and Petersen, S. E. (1990). The attention system of the human brain. *Annu. Rev. Neurosci.* 13, 25–42. doi: 10.1146/annurev.ne.13.030190.000325

Rigoli, D., Piek, J. P., Kane, R., and Oosterlaan, J. (2012). Motor coordination, working memory, and academic achievement in a normative adolescent sample: testing a mediation model. *Arch. Clin. Neuropsychol.* 27, 766–780. doi: 10.1093/arclin/acs061

Schmidt, R. A., Lee, T. D., Winstein, C., Wulf, G., and Zelaznik, H. N. (2018). Motor control and learning: a behavioral emphasis. Champaign, IL: Human Kinetics.

Schumacher, N., Schmidt, M., Wellmann, K., and Braumann, K.-M. (2018). General perceptual-cognitive abilities: age and position in soccer. *PLoS One* 13:e0202627. doi: 10.1371/journal.pone.0202627

Shaw, M. (1989). How to play badminton. Great Britain: Jorrold Colour Publicatious.

Söğüt, M., and Koçak, M. S. (2009). Coincidence timing accuracy of junior tennis players. Spor Bilimleri Dergisi: Hacettepe Üniversitesi. 1–5.

Soto, D., and Humphreys, G. W. (2007). Automatic guidance of visual attention from verbal working memory. *J. Exp. Psychol. Hum. Percept. Perform.* 33, 730–737. doi: 10.1037/0096-1523.33.3.730

Soto, D., and Humphreys, G. W. (2008). Stressing the mind: the effect of cognitive load and articulatory suppression on attentional guidance from working memory. *Percept. Psychophys.* 70, 924–934. doi: 10.3758/PP.70.5.924

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. Boston, MA: Pearson.

Thomas, J. R., Nelson, J. K., and Thomas, K. T. (1999). A generalized rank-order method for nonparametric analysis of data from exercise science: a tutorial. *Res. Q. Exerc. Sport* 70, 11–23. doi: 10.1080/02701367.1999.10607726

Tomporowski, P. D., and Pesce, C. (2019). Exercise, sports, and performance arts benefit cognition via a common process. *Psychol. Bull.* 145, 929–951. doi: 10.1037/bul0000200

Tremblay, M., Tétreau, C., Corbin-Berrigan, L.-A., and Descarreaux, M. (2022). Anthropometrics, athletic abilities and perceptual-cognitive skills associated with baseball pitching velocity in young athletes aged between 10 and 22 years old. *Front Sports Act Living* 4:822454. doi: 10.3389/fspor.2022.822454

Tsai, C.-L., Pan, C.-Y., Chen, F.-C., and Tseng, Y.-T. (2017). Open-and closed-skill exercise interventions produce different neurocognitive effects on executive functions in the elderly: a 6-month randomized, controlled trial. *Front. Aging Neurosci.* 9:294. doi: 10.3389/fnagi.2017.00294

Wang, C.-H., Tsai, C.-L., Tu, K.-C., Muggleton, N. G., Juan, C.-H., and Liang, W.-K. (2015). Modulation of brain oscillations during fundamental visuo-spatial processing: a comparison between female collegiate badminton players and sedentary controls. *Psychol. Sport Exerc.* 16, 121–129. doi: 10.1016/j.psychsport.2014.10.003

Ward, P., and Williams, A. M. (2003). Perceptual and cognitive skill development in soccer: the multidimensional nature of expert performance. *J. Sport Exerc. Psychol.* 25, 93–111. doi: 10.1123/jsep.25.1.93

Williams, A. M., and Ericsson, K. A. (2005). Perceptual-cognitive expertise in sport: some considerations when applying the expert performance approach. *Hum. Mov. Sci.* 24, 283–307. doi: 10.1016/j.humov.2005.06.002

Williams, A. M., Ward, P., Knowles, J. M., and Smeeton, N. J. (2002). Anticipation skill in a real-world task: measurement, training, and transfer in tennis. *J. Exp. Psychol. Appl.* 8, 259–270. doi: 10.1037//1076-898x.8.4.259

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Mental toughness and choking susceptibility in athletes

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Choking susceptibility refers to the propensity of an athlete to choke under pressure. Mesagno has operationalized choking susceptibility as a combination of scores on self-consciousness, anxiety and coping. Despite the potential of Mesagno's protocol, there is currently limited support for its validity. Secondly, although mental toughness (MT) has a relationship with sport performance, there is limited research on its relationship to choking under pressure, specifically. The current study investigated the relationship between choking susceptibility and mental toughness. It was hypothesized that choking susceptible athletes will have significantly lower levels of mental toughness than those who are not choking susceptible. Data from a heterogeneous sample of athletes ($N = 415$) was obtained through a Qualtrics research panel. Results of a Mann–Whitney U showed that self-reported mental toughness was not significantly different in athletes categorized as choking susceptible and non-choking susceptible. Correlational analyses also highlighted differences between mental toughness and the composite scores of choking susceptibility, which provide researchers with avenues for future research in this area alongside a need for each construct to be examined in relation to choking behavior in sport.

KEYWORDS

choking susceptibility, mental toughness, athletes, self-consciousness, anxiety, coping styles

Introduction

Success and failure are often dependent on an individual's ability to effectively perform under heightened levels of pressure. Experiencing pressure can affect how an individual performs an otherwise automatic motor task (Geukes et al., 2012; Mesagno et al., 2019; Roberts et al., 2019). For some, the pressure can often become overwhelming and result in what is known as choking under pressure (referred to as choking hereafter). Historically, there have been issues with the definition of choking (Hill et al., 2010). The initial definition of choking by Baumeister (1984, p. 610) was 'performance decrements under pressure situations' and more specifically, 'the occurrence of inferior performance despite striving and incentives for superior performance' (Baumeister and Showers, 1986, p. 361). Some researchers have argued that such definitions may fail to reflect the entire choking experience (e.g., Gucciardi and Dimmock, 2008). For example, Beilock and Gray (2007) suggest that in order for a sub-optimal performance to be considered a choke, it must be certain that the athlete was motivated to achieve their goal, was capable of performing better, and regarded the situation as important. A choke is not a random fluctuation in skill level, but rather a specific negative response to perceived pressure (Hill et al., 2010). The sources of 'perceived pressure' typically include spectators, evaluation, rewards, skill level, perceived importance, and time constraints (Cao et al., 2011; Murayama and Sekiya, 2015). These sources evoke cognitive and behavioral reactions such as distraction, self-consciousness, and anxiety, which can induce the phenomenon of choking. The existence of choking highlights the fragility of expert performance within an individual, demonstrating that constant and consistent execution in training does not guarantee skilled performance in crucial moments. Many factors have been found to influence an individual's likelihood of choking. For example, anxiety (Wilson, 2008; Clarke et al., 2020), perfectionism (Frost and Henderson, 1991; Yoon et al., 2021), and fear of negative evaluation (Mesagno et al., 2012), can interfere with one's ability to perform under pressure. Additionally, feelings of physical fatigue and heaviness, abnormal physical sensations, ego relevance, and changes in motor control have been related to an increased probability of choking (Wang, 2002; Murayama and Sekiya, 2015).

Choking susceptibility is the likelihood that an individual will experience choking (Mesagno et al., 2008). Mesagno et al. (2008, 2009) developed a protocol for identifying choking susceptibility in athletes, which is rooted in specific levels of self-consciousness (Self-Consciousness Scale; SCS; Fenigstein et al., 1975), anxiety (Sport Anxiety Scale; SAS; Smith et al., 1990), and coping styles (Coping Style Inventory for Athletes; CSIA; Anshel and Kaissidis, 1997). This protocol is currently the only method available to assess choking susceptibility, which classifies athletes as choking susceptible or choking non-susceptible based on their relative scores on these three attributes. To determine if one is choking susceptible, participants must score within the 75th-100th percentile range on at least two out of three choking susceptible inventories (based on the sample of individuals tested), and their remaining score must fall within the 50th-100th percentile range of scores surveyed. For example, to be considered choking susceptible, the participant could be relatively high (i.e., in the 75th-100th percentile) in self-consciousness (SCS) and trait anxiety (SAS), and have a positive differential CSIA score (i.e., approach coping – avoidance coping = differential score). Combining these scales to inform athletes' level of choking susceptibility has been used in previous research by Mesagno et al. (2008, 2009), Wang et al. (2004a,b), and with non-athletes (Thiessen et al., 2023). Importantly, being classified as choking susceptible does not guarantee that an athlete will choke (or that an athlete classified as non-susceptible will never choke), but rather, suggest a higher likelihood of that event occurring.

Trait anxiety may be the most obvious predictor that Mesagno et al. (2008) included in their protocol, since anxiety has consistently been linked to poor attention selection and performance (Woodman and Hardy, 2003). Anxiety research has confirmed that individuals high in trait anxiety react to pressure situations with greater levels of state anxiety than individuals low in trait anxiety (e.g., Spielberger et al., 1976; Horikawa and Yagi, 2012). It has been reported that this effect happens because high trait anxious individuals respond to pressure with elevated state anxiety more frequently or intensely, which ultimately affects their performance under pressure (Byrne and Eysenck, 1995). Furthermore, high trait anxiety overwhelms working memory which causes inefficient processing and promotes choking (Wilson et al., 2007). Likewise, high trait anxious athletes are susceptible to choking via self-focus mechanisms as they also tend to have high dispositional reinvestment (Masters et al., 1993). Similarly, coping ability is consistently found to influence performance under pressure in sport (Anshel, 1996; Wang et al., 2004a; Nicholls and Polman, 2007). Avoidance-based coping (i.e., directing activity away from threat) has been found to be a beneficial coping style under stress (Madden et al., 1990; Anshel, 1997). Alternatively, approach-based coping (i.e., directing activity toward threat) can result in the performer consciously controlling behavior during stress, which is known to decrease performance and result in a choke (Baumeister, 1984; Wang et al., 2004a). Consistent with this conceptualization, Diotaiuti et al. (2021) found that an approach coping style appeared to have the greatest negative effect on archer athletes brooding activity. Lastly, self-consciousness is known to be negatively related to performance. In a series of studies, Geukes et al. (2013a,b) found that self-consciousness negatively affected performance in high pressure conditions, and that lower self-consciousness was related to better performance in high pressure conditions, but not low-pressure conditions. Wang et al. (2004b) found that self-conscious athletes were more susceptible to choking.

Since Mesagno et al. (2008) defined choking susceptibility, researchers have examined linkages between this conceptualization and other constructs. For example, Mesagno and Marchant (2013) investigated the cognitive processes associated with choking susceptible and choking resistant athletes in a mixed-method approach. The authors designed a pressured task (i.e., netball shots with audience presence, performance-contingent financial incentives, and video recorded shot attempts), and reported that the cognitions associated with choking susceptibility included emotion-focused attention (e.g., fear, embarrassment, worry) and approach-cognitive coping strategies (e.g., public self-awareness), psychodynamic defense mechanisms (i.e., projection), whereas choking resistance was associated with task-focused attention (e.g., self-talk) and avoidance-cognitive coping strategies (e.g., blocking out distractions, imagining team support). Additionally, those considered to be choking susceptible experienced a decrease in performance (i.e., less accurate and more inconsistent) during the pressure manipulation compared to those who were considered choking resistant. Choking susceptibility has also been found to be related to handedness (Mesagno et al., 2019), dominant left-hemispheric activation (Hatfield et al., 2013), and personality traits (e.g., neuroticism, perfectionism, etc.; Frost and Henderson, 1991; Thiessen et al., 2023). Mesagno et al.'s choking susceptibility protocol is the only procedure available to measure choking susceptibility to date.

Empirical evidence has linked choking susceptibility with various outcomes that are both related to performance under pressure and consistent with the conceptual foundations for Mesagno et al.'s (2008) operational definition of the construct. However, more evidence is needed to support choking susceptibility's concurrent and predictive validity since surprisingly, there is little evidence available that it is related to choking. The current study aims to further support the concurrent validity of choking susceptibility by examining how it is related to mental toughness.

Mental toughness is a term typically applied to athletes who perform well in pressurized circumstances (Liew et al., 2019; Bédard Thom et al., 2021). It has been called a "critical success factor" (Cowden, 2017, p. 1) because it is believed to facilitate adaptive responses to positive (e.g., success) and negative (e.g., failure) forms of stress (e.g., competition pressure). According to Gucciardi et al. (2017), mental toughness is "a state-like psychological resource that is purposeful, flexible and efficient in nature for the enactment and maintenance of goal directed pursuits" (p. 18). Although debate surrounding the conceptualization of mental toughness continues (i.e., stability, different types) much of the research to date supports that it is a malleable, psychological quality that is greatly dependent on self-belief/confidence and perceived self-control in the face of challenges and stressors (Bédard Thom et al., 2021). Excellent coping strategies and perseverance would appear to link mental toughness with successful performance (Bell et al., 2013; Gucciardi et al., 2016; Cowden, 2017; Lin et al., 2017; Giles et al., 2018; Gucciardi et al., 2021). For example, Bell et al. (2013) developed and delivered a mental toughness intervention for elite cricket players that enhanced their ability to perform under pressure, specifically in their batting and fitness performance. There is also evidence suggesting that athletes with higher mental toughness can more quickly initiate performance enhancing states (i.e., flow and clutch states) during sport competition (Jackman et al., 2020).

Given that mental toughness is associated with excelling under pressure, theoretically, mental toughness could be related to choking susceptibility. Hill and colleagues published a series of studies involving the nature of mental toughness relative to choking. A focus group of sport psychologists concluded that lower mental toughness is linked to the probability of choking, and that sport psychologists should prioritize its development to reduce the probability and impact of choking (Hill et al., 2009). Another study by Hill et al. (2010) purposefully sampled elite golfers ($N=6$) who believed they "often choked under pressure," compared to golfers who appeared to "excel under pressure" ($N=5$), as well as elite coaches who had worked with both groups ($N=4$). Following semi-structured interviews, the authors found that that those who were more prone to choking appeared to have lower mental toughness than those who were categorized as golfers who excel under pressure (Hill et al., 2010). However, mental toughness was not directly assessed in these studies, and prevalence of choking was based on participants' self-perceptions, not Mesagno et al.'s (2008) operational definition or measured choking behavior.

According to Mesagno's protocol, using more avoidance than approach strategies will work to prevent choking under pressure (Wang et al., 2004a). However, research has shown that, for the most part, avoidance coping strategies are associated with choking under pressure and approach strategies may encourage clutch performance (Hill and Hemmings, 2015). For example, Hill et al. (2010) explains that chokers predominantly use avoidance strategies (e.g., rushing through shots) to cope, however, this is not the case for those who excelled; they tended to reduce or manage the stressors through problem-focused or approach coping (e.g., process goals and preparation). This discrepancy could in part be due to the different instruments used in the coping literature but may also be the result of avoidance strategies offering individuals immediate emotion regulation in the short term, which can encourage positive behavioral outcomes (e.g., Hayes et al., 1996) but are less effective in the long term (Hill and Hemmings, 2015). In terms of the relationship between coping and mental toughness, Nicholls et al. (2008) found that mental toughness was more strongly associated with the use of approach coping strategies (i.e., task-oriented coping strategies such as thought control, mental imagery, relaxation, effort expenditure, logical analysis, and seeking support) compared to avoidant strategies (i.e., distraction-orientated coping such as distancing and mental distraction, or disengagement-orientated coping such as disengagement/resignation and venting of unpleasant emotions) in athletes. Madrigal et al. (2017) found that mentally tougher collegiate athletes reported the use of more problem and emotion focused coping strategies rather than avoidant coping strategies. To our knowledge, no research has assessed the relationship between mental toughness and scores on the CSIA used in Mesagno's protocol. Self-consciousness (and the related concept of self-awareness) have also been linked to mental toughness. Mentally tougher competitive tennis players have been found to have greater levels of self-awareness (Cowden, 2017), and researchers have found that mental toughness is related to dispositional flow which includes an ability to lose consciousness aware (i.e., concern for the opinion of others disappears; Crust and Swann, 2013; Jackman et al., 2017). Consistent with these findings, the pressure of being watched by others (a common manipulation to increase performance pressure) increases self-consciousness and self awareness (DeCaro et al., 2011).

The relationship between mental toughness and anxiety is somewhat inconsistent, yet self-belief and self-confidence is the most commonly reported psychological attribute associated with athlete mental toughness (e.g., Gucciardi et al., 2015; Bédard Thom et al., 2021). Athletes can experience anxiety when they lack confidence or self-efficacy in their ability to perform successfully in a threatening or taxing situation; they believe that they are incapable of managing potentially detrimental events (Chase et al., 2005). Thus, mentally tougher athletes are expected to report somewhat lower levels of sport trait anxiety (Mojtahedi et al., 2023), which will expectedly contribute to lower choking susceptibility.

The purpose of this study was to determine if there will be a difference between choking susceptible and choking non-susceptible athletes' level of mental toughness. Based on conceptualizations of mental toughness and choking susceptibility, and research linking them to performance under pressure, we hypothesized that choking susceptible athletes will report lower levels of mental toughness than choking non-susceptible athletes.

Method

Participants

Using Qualtrics, athletes across Canada and the United States of America were recruited to participate in the online study. We requested our target audience (i.e., athletes in North America above the age of 18 years old) from Qualtrics who found a representative sample from their proprietary online sample. Qualtrics completed all recruitment and distribution of the survey to participants. All data was stored on Qualtrics' secure platform during collection. Once data was collected, Qualtrics sent us a data scrub report where they outlined what participants could be removed due to lack of data, straightening, etc. Final removal of participants was ultimately made by the researchers. The questionnaires were blocked into separate pages throughout the survey for participant ease of use and items of each questionnaire were presented in a matrix. For inclusion to participate, individuals must have been 18 years or older and participate in a sport. No other inclusion or exclusion criteria were applied. Participants were compensated through the vendors who partner with Qualtrics. Participants agree upon a set compensation before taking part in the survey which could be in the form of points, airline miles, etc.

We obtained a total of 425 responses and of that total, 10 were removed due to straightlining and lack of sport clarification. Therefore, the final sample size was 415 participants, with a total of 187 females, 224 males, 3 non-binary/third gender, and 1 participant that preferred not to indicate gender. Participants' age ranged from 18–80, with an average age of 40.56. Only 316 valid responses for age were given. Competitive athletes were defined by those who indicated they participated in international (n = 9), national (n = 28), provincial/state (n = 53), university/college (n = 45), and intermediate (n = 72) levels of sport. Participants were from 39 different sports. The most common sports included basketball (n = 91), soccer (n = 40), football (n = 34), tennis (n = 32), golf (n = 30), softball (n = 24), baseball (n = 23), and volleyball (n = 18). Additionally, participants were asked to indicate whether or not they were starters in their respective sport; 79.4% reported being a regular or occasional starter.

Procedure

Prior to recruitment and data collection, ethical clearance was granted by Brock University's Research Ethics Board 21–274. Data was collected between July–August 2022. The choking susceptibility protocol comprises the SCS (Fenigstein et al., 1975), the SAS (Smith et al., 1990), and the CSIA (Anshel and Kaissidis, 1997).

Measures

Questionnaires measured participant demographic information, mental toughness, and choking susceptibility. Demographics included questions regarding gender, age, ethnicity, and athletic status. Choking susceptibility was determined using a combination of measures examining self-consciousness, trait anxiety, and coping styles. A unidimensional measure was used to assess sport mental toughness.

Self-consciousness scale

The 23-item Self-Consciousness Scale (Fenigstein et al., 1975) measures three distinct subscales of self-consciousness (i.e., private self-consciousness, public self-consciousness, and social anxiety). Items are rated on a scale of 0 (*extremely uncharacteristic*) to 4 (*extremely characteristic*) where those with higher scores report higher levels of public self-consciousness, private self-consciousness, and social anxiety. Acceptable internal consistency ($\alpha > 0.73$) has been reported for all subscales (Fenigstein et al., 1975). In a sample of athletes, the public self-consciousness subscale had a Cronbach's alpha of 0.75, private self-consciousness had a Cronbach's alpha of 0.70, and social anxiety had 0.80 (Hatzigeorgiadis, 2002); Cronbach's alpha for the scales global factor, which was used for this protocol, was 0.84 with the current data. There is also considerable evidence for both the construct and discriminant validity of the distinct subscales of self-consciousness (Fenigstein, 1987).

Sport anxiety scale

To assess trait anxiety, the 21-item Sport Anxiety Scale (Smith et al., 1990) was used. The SAS is made up of three subscales that specifically measure somatic anxiety, worry, and concentration disruption. Statements and responses are based on a 4-point Likert scale, ranging from 1 (*not at all*) to 4 (*very much so*). Total scores range from 21 to 84, with higher scores indicating high trait anxiety. The SAS has shown good internal consistency results and adequate validity in athletes (Smith et al., 1990; Dunn et al., 2000). The Cronbach's alpha for the total scale was 0.96 with the present data.

Coping style inventory for athletes

The Coping Style Inventory for Athletes (Anshel and Kaissidis, 1997) is a 16-item questionnaire used to measure participants' approach and avoidance coping strategies on a 5-point Likert scale. Responses range from 1 (*very untrue*) to 5 (*very true*). Total scores range from 8 to 40 on each of the two subscales, and higher scores indicate a greater propensity to use that particular coping style. High construct and predictive validity have been reported for the scale, as well as acceptable internal consistency in a sample of athletes (Kaissidis-Rodafinos et al., 1997); the current data showed Cronbach's alphas ranging from 0.67–0.76. For the choking susceptibility protocol, the differential score is calculated by taking the total avoidance coping score and subtracting it from the total approach coping score (e.g., Mesagno et al., 2008).

Mental toughness index

The Mental Toughness Index (MTI; Gucciardi et al., 2015) is an 8-item unidimensional measure of mental toughness.[1] The MTI instructs participants to indicate how they typically think, feel, and behave as an athlete. The MTI is rated on a 7-point Likert scale (*false, 100% of the time; true, 100% of the time*). The MTI was intentionally developed to bring together the most common attributes of mental toughness across the field, and to be conceptually distinct from other similar constructs that are also known to be influential on sport performance such as Grit, Resilience and Hardiness (Gucciardi et al., 2015). The MTI has also demonstrated cross-cultural invariance in athlete samples (Stamatis et al., 2021). In support of the MTI's construct validity, Gucciardi et al. (2015) demonstrated excellent fit using CFA across three independent samples that were purposefully selected to represent different achievement contexts (i.e., athletes, post-secondary students, and "white collar" workers). They also reported excellent composite reliabilities for the scale in these samples (ρ = 0.86 to 0.89). Cronbach's alpha with the current data was 0.90. In a recent systematic review of mental toughness measures, the MTI received among the highest ratings, including sufficient ratings for structural validity and internal consistency and the most positive results for hypothesis testing (Farnsworth et al., 2020).

Statistical analysis

As the research question was to compare choking susceptible and choking non-susceptible athletes on mental toughness, the data analysis plan primarily comprised independent samples t-test on mental toughness. Prior to this analysis, assumptions (e.g., normal distribution and homogeneity of variance) would be checked. If assumptions were not upheld, a non-parametric group comparison would be employed. Furthermore, a Confirmatory Factor Analysis (CFA) of the mental toughness measure would be used to ensure that the model structure fit the current data. Finally, supplementary analysis

1 http://www.danielgucciardi.com.au/questionnaires.html

would be employed to see if choking susceptibility may differ by factors such as gender, level of competition and experience of the sample.

Data were analyzed using SPSS 26; the factor analysis was conducted using EQS 6.4. The procedure in the current analyses that required the largest sample size was the CFA of the MTI. Tabachnick and Fidell (2021) suggest that sample sizes of over 300 are adequate when communalities in the data are high, there are a small number of factors, and at least four items for each factor, all of which were present in the current data. A power analysis using G*Power for a two tailed Mann Whitney U with an alpha of 0.05 and power of 0.95 and moderate effect size suggests a total sample size of 220. Using these criteria, our current sample size of 415 was adequate for the CFA and all subsequent analyses.

Results

Individuals in the current sample who scored over the 75th percentile on 2 out of the 3 choking susceptible questionnaires and scored over the 50th percentile on the remaining choking susceptibility questionnaire were considered choking susceptible. As there were no observations at the 75th percentile cut-off within our data, the nearest one (73rd percentile) was used for our analyses. Out of the sample, 16% ($n=67$) were considered choking susceptible and 84% ($n=348$) were choking non-susceptible. Table 1 summarizes these samples by demographic characteristics.

Participant descriptives

A confirmatory factor analysis was conducted on the MTI to determine if the current data fit to the one factor model. Table 2 gives the descriptive statistics and correlations among the eight MTI items. The data upheld the assumptions of normal distribution and absence of multicollinearity (e.g., correlations >0.90). However, the normalized Mardia's coefficient indicated multivariate kurtosis, so the robust goodness of fit indicators were interpreted. The chi-square for the model was significant [$\chi^2_{(20)}=77.10$, $p<0.001$], but this is known to be influenced by large sample size. Other goodness of fit indicators showed good fit of the data to the model, CFI = 0.95, IFI – 0.96, RMSEA = 0.08. Acceptable criteria for good fit are >0.95 for the CFI and IFI and < 0.08 for the RMSEA. All eight MTI items loaded significantly on the global MTI factor. The Cronbach's alpha for this factor was 0.90.

Correlations between the MTI and the choking susceptibility scales revealed that mental toughness was uncorrelated to self-consciousness ($r=0.03$), but significantly correlated to sport anxiety ($r=-0.31$) and the differential coping score ($r=-0.18$) in the expected directions based on this protocol. Among the two coping styles, the MTI was significantly correlated to avoidance coping ($r=0.15$) but not significantly correlated to approach coping ($r=-0.04$).

TABLE 1 Participant descriptives.

	Choking susceptible	Choking non-susceptible
n	67	348
Mean Age	35.76	41.62
Male	47%	55%
Caucasian	67%	63%
Competitive	62%	47%
Starters	46%	46%

The distribution of the MTI was not normal for both choking susceptible ($KS_{(67)}=0.12$, $p>0.05$) and non-susceptible athletes ($KS_{(348)}=0.08$, $p>0.05$), and a Levene's test revealed that the MTI did not uphold the assumption of homogeneity of variance. Therefore, a Mann–Whitney U was used to examine if there was a difference in MTI scores between choking susceptible [$n=67$; $M=42.94$ (6.64)] and non-susceptible [$n=348$; $M=43.83$ (8.14)]. The result was non-significant [$U_{(415)}=10826.00$ $p>0.05$] with an effect size of 0.11. Therefore, no difference in MTI scores were found across the two groups of athletes classified as either choking non-susceptible or choking susceptible.

Given the heterogeneous nature of the sample, several supplementary analyses were conducted. In particular, we were interested in the potential role of gender, experience, and level of competition in the choking susceptible-mental toughness relationship. However, as noted above the data required non-parametric analyses and it is not possible to do factorial non-parametric analyses. Chi square analyses were used to examine if proportion of choking susceptible individuals differed by gender, level of experience, and competition. There was no significant difference in prevalence of choking susceptibility between males and females, or between individuals with less than ($n=182$) and greater than 5 years experience ($n=233$). There was a significant effect for level of competition on probability of choking susceptibility. Specifically, 12.5% of recreational athletes were choking susceptible whereas 19.8% of competitive athletes were. This difference in proportions was statistically significant [$\chi^2_{(1)}=4.09$, $p<0.05$, $\varphi=-0.10$].

Discussion

The current study examined if athletes designated as choking susceptible as per Mesagno et al.'s (2008, 2009) protocol differed in their level of mental toughness from those designated as non-choking susceptible. Our hypotheses were not supported. No significant difference was found between those categorized as choking susceptible and choking non-susceptible on the MTI. This finding is inconsistent with anecdotal evidence and conceptual arguments (e.g., Hill et al., 2009, 2019) that suggest that choking susceptible athletes are more likely to be 'less mentally tough' than those who are not choking susceptible. However, the results of the current study are not necessarily inconsistent with empirical literature that has conceptualized mental toughness or examined mental toughness in relation to sport performance/performance under pressure (e.g., Gucciardi et al., 2015; Bédard Thom et al., 2021). The distinctness and inconsistencies presented here between mental toughness and choking susceptibility raise interesting questions about this relationship and call into question the validity of an assumed relationship between the two (Hill et al., 2009, 2019).

The current analyses suggest that choking susceptibility and mental toughness are distinct constructs. There were no significant differences on MTI scores between athletes who were choking susceptible and those

TABLE 2 Correlation matrix and descriptive statistics of MTI items.

Item	MTI1	MTI2	MTI3	MTI4	MTI5	MTI6	MTI7	MTI8
MTI2	0.65*							
MTI3	0.56*	0.60*						
MTI4	0.53*	0.55*	0.56*					
MTI5	0.53*	0.52*	0.60*	0.66*				
MTI6	0.46*	0.45*	0.48*	0.43*	0.51*			
MTI7	0.54*	0.53*	0.47*	0.57*	0.56*	0.55*		
MTI8	0.42*	0.43*	0.46*	0.43*	0.46*	0.59*	0.55*	---
M *SD*	5.52 1.31	5.29 1.31	5.18 1.35	5.62 1.33	5.55 1.34	5.40 1.25	5.55 1.21	5.58 1.30

*$p < 0.001$.

who were not, suggesting that they come from the same population with respect to the attribute of mental toughness. Correlational analyses showed that MTI scores were uncorrelated with one of the three composite items of choking susceptibility (i.e., self-consciousness). Furthermore, its correlations with coping style and anxiety showed small and moderate effect sizes, respectively (Field, 2017). Whereas this is the first study to directly examine choking susceptibility and mental toughness, previous research has examined the associations between mental toughness and the composite constructs that comprise Mesagno et al.'s choking susceptibility protocol and found similar results. Some researchers have supported a negative relationship between mental toughness and anxiety (Schaefer et al., 2016; Kristjánsdóttir et al., 2019; Mojtahedi et al., 2023), but others have found no relationship (Cowden, 2017) and even a positive association between trait anxiety and mental toughness (Hardy et al., 2014). Whereas coping style has been found to be related to mental toughness (e.g., Poulus et al., 2020), very little literature has linked mental toughness to self-consciousness. Within the context of this literature, we would suggest that the present results provide support to the notion that choking susceptibility and mental toughness are distinct but related constructs.

It is possible that any relationship between choking susceptibility and mental toughness may be more nuanced than the present design was able to ascertain. Our sample was a diverse one with respect to experience, level of competition, and gender. While the overall finding was that choking susceptibility did not affect mental toughness with this sample, it is possible that there still may be a relationship between the two constructs, as the literature suggests. For example, in our sample, the prevalence of choking susceptibility was significantly higher in competitive athletes than recreational athletes. It is possible that there may be a significant difference in mental toughness between choking susceptible and non-susceptible athletes at different competitive levels. Furthermore, although we found no gender differences in choking susceptibility, given that there are often research gender differences in mental toughness (e.g., Nicholls and Polman, 2007; Madrigal et al., 2017), it is possible that the choking susceptibility-mental toughness relationship may differ by gender. In summary, we suggest that while we concluded that the constructs of choking susceptibility and mental toughness are separate but related, we acknowledge that it is possible that they may be related in specific samples (e.g., all competitive athletes, or all male athletes).

Furthermore, it may be that mental toughness is not related to choking susceptibility but isrelated to choking. It must be recognized that choking susceptibility is distinct from actual choking or performance under pressure, and that both of these later factors are more widely studied in sport psychology. Many of the associated factors noted in the introduction (e.g., anxiety, coping styles) are related to actual choking, not just choking susceptibility, and choking susceptibility has not yet been empirically linked to actually choking under pressure. Therefore, finding that mental toughness is not related to choking susceptibility may be mutually exclusive of any relationship between mental toughness and choking under pressure. This would be consistent with studies like, Hill et al. (2009, 2010), Bell et al. (2013) as well as Gucciardi et al. (2016) and Giles et al. (2018), which have suggested that mental toughness may influence performance under pressure. Again, we would suggest that there is much research to be done in this area, particularly with respect to the construct validity of choking susceptibility.

Finally, our findings of relatively minimal overlap between choking susceptibility and mental toughness may have serious implications for the construct validity of choking susceptibility, which is the newer and less well supported of the two constructs. The choking susceptibility protocol by Mesagno et al. (2008, 2009) is still in its infancy; it is unknown whether the protocol can accurately predict choking behaviors. The protocol consists of self-consciousness, trait anxiety, and coping style inventories to measure choking susceptibility. These psychological inventories have been linked to performance and ultimately choking under pressure (Mesagno, 2006). However, Mesagno admits that other factors may also influence choking susceptibility, such as introversion (Anshel, 1997). Furthermore, Mesagno recognizes that choking can be viewed as a continuum, nevertheless, Mesagno deliberately made a stringent selection criterion to purposively sample participants on opposite ends of the performance under pressure experience (Mesagno, 2006).

Limitations and future directions

In addition to the above limitations on choking susceptibility, our hypotheses may not have been supported due to the chosen mental toughness scale. Although the MTI appears to be a measure with strong psychometric properties (Gucciardi et al., 2015), there is still much work to do with respect to understanding the conceptual clarity and mechanisms of mental toughness, for example its antecedents and outcomes and how practitioners, coaches and athletes can develop this quality over time. Furthermore, we did not ask participants' additional information about their sport such as time spent practicing or number of competitions. We recognize that these variables and potentially others could have affected the results. Lastly, as noted above, the choking susceptibility protocol by Mesagno et al. (2008, 2009) is still in its infancy within the realm of investigating connections with performance tendencies under pressure. The protocol has not yet confirmed that it can accurately predict choking behavior in individuals. Therefore, if we were to measure performance in the current study, the results may not necessarily have given us practical data. Finally, there are potential limitations to a cross-sectional design, and online survey, as the current design employed. We acknowledge that such design features may have affected the representativeness of the sample as well as potential response biases in ways that other designs may minimize.

Future research should determine whether the choking susceptibility protocol can successfully predict choking under pressure in athletes while comparing performance under different levels of pressure. The causes and characteristics that may predispose athletes to choking can help sport psychologists prevent a possible choke. We believe that this is essential prior to examining if choking susceptible and choking resistant individuals differ on variables such as mental toughness.

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 Brock University Research Ethics 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

BT: Writing – review & editing, Writing – original draft, Investigation, Data curation. MB: Writing – review & editing, Writing – original draft, Methodology. PS: Writing – original draft, Writing – review & editing, Supervision, Formal analysis, Conceptualization.

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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.

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References

Anshel, M. H. (1996). Coping styles among adolescent competitive athletes. *J. Soc. Psychol.* 136, 311–323. doi: 10.1080/00224545.1996.9714010

Anshel, M. H. (1997). Sport psychology: From theory to practice. *3rd* Edn. Scottsdale, AZ: Gorsuch Scarisback.

Anshel, M. H., and Kaissidis, A. N. (1997). Coping style and situational appraisals as predictors of coping strategies following stressful events in sport as a function of gender and skill level. *Br. J. Psychol.* 88, 263–276. doi: 10.1111/j.2044-8295.1997.tb02634.x

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

Baumeister, R. F., and Showers, C. J. (1986). A review of paradoxical performance effects: choking under pressure in sports and mental tests. *Eur. J. Soc. Psychol.* 16, 361–383. doi: 10.1002/ejsp.2420160405

Bédard Thom, C., Guay, F., and Trottier, C. (2021). Mental toughness in sport: the goal-expectancy-self-control (Ges) model. *J. Appl. Sport Psychol.* 33, 627–643. doi: 10.1080/10413200.2020.1808736

Bell, J. J., Hardy, L., and Beattie, S. (2013). Enhancing mental toughness and performance under pressure in elite young cricketers: a 2-year longitudinal intervention. *Sport Exerc. Perform. Psychol.* 2, 281–297. doi: 10.1037/a0033129

Beilock, S. L., and Gray, R. (2007). Why do athletes choke under pressure? In *Handbook of sport psychology*. (Eds.) G. Tenenbaum and R. C. Eklund, 3rd ed. John Wiley & Sons, Inc., 425–444

Byrne, A., and Eysenck, M. W. (1995). Trait anxiety, anxiety mood, and threat detection. *Cognit. Emot.* 9, 549–562. doi: 10.1080/02699939508408982

Cao, Z., Price, J., and Stone, D. F. (2011). Performance under pressure in the NBA. *J. Sports Econ.* 12, 231–252. doi: 10.1177/1527002511404785

Chase, M. A., Magyar, T. M., and Drake, B. M. (2005). Fear of injury in gymnastics: self-efficacy and psychological strategies to keep on tumbling. *J. Sports Sci.* 23, 465–475. doi: 10.1080/02640410400021427

Clarke, P., Sheffield, D., and Akehurst, S. (2020). Personality predictors of yips and choking susceptibility. *Front Psychol* 10:2784. doi: 10.3389/fpsyg.2019.02784

Cowden, R. G. (2017). Mental toughness and success in sport: a review and prospect. *Open Sports Sci. J.* 10, 1–14. doi: 10.2174/1875399X01710010001

Crust, L., and Swann, C. (2013). The relationship between mental toughness and dispositional flow. *Eur. J. Sport Sci.* 13, 215–220. doi: 10.1080/17461391.2011.635698

DeCaro, M. S., Thomas, R. D., Albert, N. B., and Beilock, S. L. (2011). Choking under pressure: multiple routes to skill failure. *J. Exp. Psychol. Gen.* 140, 390–406. doi: 10.1037/a0023466

Diotaiuti, P., Corrado, S., Mancone, S., Falese, L., Dominski, F. H., and Andrade, A. (2021). An exploratory pilot study on choking episodes in archery. *Front. Psychol.* 12:585477. doi: 10.3389/fpsyg.2021.585477

Dunn, J. G. H., Causgrove-Dunn, J., Wilson, P., and Syrotuik, D. G. (2000). Reexamining the factorial composition and factor structure of the sport anxiety scale. *J. Sport Exerc. Psychol.* 22, 183–193. doi: 10.1123/jsep.22.2.183

Farnsworth, J. L., Marshal, A., and Myers, N. L. (2020). Mental toughness measures: a systematic review of measurement properties for practitioners. *J. Appl. Sport Psychol.* 34, 479–494. doi: 10.1080/10413200.2020.1866710

Fenigstein, A. (1987). On the nature of public and private self-consciousness. *J. Pers.* 55, 543–554. doi: 10.1111/j.1467-6494.1987.tb00450.x

Fenigstein, A., Scheier, M. F., and Buss, A. H. (1975). Public and private self-consciousness: assessment and theory. *J. Consult. Clin. Psychol.* 43, 522–527. doi: 10.1037/h0076760

Field, A. (2017). Discovering statistics using IBM SPSS statistics. *5th* Edn. Thousand Oaks, CA: Sage Publications.

Frost, R. O., and Henderson, K. J. (1991). Perfectionism and reactions to athletic competition. *J. Sport Exerc. Psychol.* 13, 323–335. doi: 10.1123/jsep.13.4.323

Geukes, K., Mesagno, C., Hanrahan, S. J., and Kellmann, M. (2012). Testing an interactionist perspective on the relationship between personality traits and performance under public pressure. *Psychol. Sport Exerc.* 13, 243–250. doi: 10.1016/j.psychsport.2011.12.004

Geukes, K., Mesagno, C., Hanrahan, S. J., and Kellmann, M. (2013a). Activation of self-focus and self-presentation traits under private, mixed, and public pressure. *J. Sport Exerc. Psychol.* 35, 50–59. doi: 10.1123/jsep.35.1.50

Geukes, K., Mesagno, C., Hanrahan, S. J., and Kellmann, M. (2013b). Performing under pressure in private: activation of self-focus traits. *Int. J. Sport Exerc. Psychol.* 11, 11–23. doi: 10.1080/1612197X.2012.724195

Gucciardi, D. F., Lines, R. L. J., Ducker, K. J., Peeling, P., Chapman, M. T., and Temby, P. (2021). Mental toughness as a psychological determinant of behavioral perseverance in special forces selection. *Sport, Exercise, and Performance Psychology.* 10, 164–175. doi: 10.1037/spy0000208

Giles, B., Goods, P. S. R., Warner, D. R., Quain, D., Peeling, P., Ducker, K. J., et al. (2018). Mental toughness and behavioural perseverance: a conceptual replication and extension. *J. Sci. Med. Sport* 21, 640–645. doi: 10.1016/j.jsams.2017.10.036

Gucciardi, D. F., and Dimmock, J. A. (2008). Choking under pressure in sensorimotor skills:conscious processing or depleted attentional resources? *Psychol. Sport Exerc.* 9, 45–59. doi: 10.1016/j.psychsport.2006.10.007

Gucciardi, D. F., Hanton, S., and Fleming, S. (2017). Are mental toughness and mental health contradictory concepts in elite sport? A narrative review of theory and evidence. *J. Sci. Med. Sport* 20, 307–311. doi: 10.1016/j.jsams.2016.08.006

Gucciardi, D. F., Hanton, S., Gordon, S., Mallett, C. J., and Temby, P. (2015). The concept of mental toughness: tests of dimensionality, nomological network, and traitness. *J. Pers.* 83, 26–44. doi: 10.1111/jopy.12079

Gucciardi, D. F., Peeling, P., Ducker, K. J., and Dawson, B. (2016). When the going gets tough: mental toughness and its relationship with behavioural perseverance. *J. Sci. Med. Sport* 19, 81–86. doi: 10.1016/j.jsams.2014.12.005

Hardy, L., Bell, J., and Beattie, S. (2014). A neuropsychological model of mentally tough behaviour. *J. Pers.* 82, 69–81. doi: 10.1111/jopy.12034

Hatfield, B. D., Costanzo, M. E., Goodman, R. N., Lo, L. C., Oh, H., Rietschel, J. C., et al. (2013). The influence of social evaluation on cerebral cortical activity and motor performance: a study of "real-life" competition. *Int. J. Psychophysiol.* 90, 240–249. doi: 10.1016/j.ijpsycho.2013.08.002

Hatzigeorgiadis, A. (2002). Thoughts of escape during competition: relationships with goal orientations and self-consciousness. *Psychol. Sport Exerc.* 3, 195–207. doi: 10.1016/S1469-0292(01)00039-5

Hayes, S. C., Wilson, K. G., Gifford, E. V., Follette, V. M., and Strosahl, K. (1996). Experiential avoidance and behavioral disorders: A functional dimensional approach to diagnosis and treatment. *Journal of Consulting and Clinical Psychology* 64, 1152–1168. doi: 10.1037/0022-006X.64.6.1152

Hill, D. M., Cheesbrough, M., Gorczynski, P., and Matthews, N. (2019). The consequences of choking in sport: a constructive or destructive experience? *Sport Psychol.* 33, 12–22. doi: 10.1123/tsp.2018-0070

Hill, D. M., Hanton, S., Fleming, S., and Matthews, N. (2009). A re-examination of choking in sport. *Eur. J. Sport Sci.* 9, 203–212. doi: 10.1080/17461390902818278

Hill, D. M., Hanton, S., Matthews, N., and Fleming, S. (2010). A qualitative exploration of choking in elite golf. *J. Clin. Sport Psychol.* 4, 221–240. doi: 10.1123/jcsp.4.3.221

Hill, D. M., and Hemmings, B. (2015). A phenomenological exploration of coping responses associated with choking in sport. *Qual. Res. Sport Exerc. Health* 7, 521–538. doi: 10.1080/2159676X.2014.981573

Horikawa, M., and Yagi, A. (2012). The relationships among trait anxiety, state anxiety and the goal performance of penalty shoot-out by university soccer players. *PlosOne* 7:e35727. doi: 10.1371/journal.pone.0035727

Jackman, P. C., Crust, L., and Swann, C. (2017). Further examining the relationship between mental toughness and dispositional flow in sport: a mediation analysis. *Int. J. Sport Psychol.* 48, 356–374. doi: 10.7352/IJSP.2017.48.356Jackman

Jackman, P. C., Crust, L., and Swann, C. F. J. (2020). The role of mental toughness in the occurrence of flow and clutch states in sport. *Int. J. Sport Psychol.* 51, 1–27. doi: 10.7352/IJSP.2020.51.001

Kaissidis-Rodafinos, A., Anshel, M. H., and Porter, A. (1997). Personal and situational factors that predict coping strategies for acute stress among basketball referees. *J. Sports Sci.* 15, 427–436. doi: 10.1080/026404197367218

Kristjánsdóttir, H., Jóhannsdóttir, K. R., Pic, M., and Saavedra, J. M. (2019). Psychological characteristics in women football players: skills, mental toughness, and anxiety. *Scand. J. Psychol.* 60, 609–615. doi: 10.1111/sjop.12571

Liew, G. C., Kuan, G., Chin, N. S., and Hashim, H. A. (2019). Mental toughness in sport. *Ger. J. Exerc. Sport Res.* 49, 381–394. doi: 10.1007/s12662-019-00603-3

Lin, Y., Mutz, J., Clough, P. J., and Papageorgiou, K. A. (2017). Mental toughness and individual differences in learning, educational and work performance, psychological well-being, and personality: a systematic review. *Front. Psychol.* 8:1345. doi: 10.3389/fpsyg.2017.01345

Madden, C. C., Summers, J. J., and Brown, D. F. (1990). The influence of perceived stress on coping with competitive basketball. *Int. J. Sport Psychol.* 21, 21–35.

Madrigal, L., Gill, D. L., and Willse, J. T. (2017). Gender and the relationships among mental toughness, hardiness, optimism and coping in collegiate athletics: A structural equation modeling approach. *Journal of Sport Behavior* 40, 68–86.

Masters, R. S. W., Polman, R. C. J., and Hammond, N. V. (1993). 'Reinvestment': a dimension of personality implicated in skill breakdown under pressure. *Personal. Individ. Differ.* 14, 655–666. doi: 10.1016/0191-8869(93)90113-H

Mesagno, C. (2006). Investigating the use of choking intervention strategies with choking- susceptible athletes. Doctoral dissertation. Melbourne: Victoria University.

Mesagno, C., Garvey, J., Tibbert, S. J., and Gropel, P. (2019). An investigation into handedness and choking under pressure in sport. *Res. Q. Exerc. Sport* 90, 217–226. doi: 10.1080/02701367.2019.1588935

Mesagno, C., Harvey, J. T., and Janelle, C. M. (2012). Choking under pressure: the role of fear of negative evaluation. *Psychol. Sport Exerc.* 13, 60–68. doi: 10.1016/j.psychsport.2011.07.007

Mesagno, C., and Marchant, D. (2013). Characteristics of polar opposites: an exploratory investigation of choking-resistant and choking-susceptible athletes. *J. Appl. Sport Psychol.* 25, 72–91. doi: 10.1080/10413200.2012.664605

Mesagno, C., Marchant, D., and Morris, T. (2008). A pre-performance routine to alleviate choking in "choking-susceptible" athletes. *Sport Psychol.* 22, 439–457. doi: 10.1123/tsp.22.4.439

Mesagno, C., Marchant, D., and Morris, T. (2009). Alleviating choking: the sounds of distraction. *J. Appl. Sport Psychol.* 21, 131–147. doi: 10.1080/10413200902795091

Mojtahedi, D., Dagnall, N., Denovan, A., Clough, P., Dewhurst, S., Hillier, M., et al. (2023). Competition anxiety in combat sports and the importance of mental toughness. *Behav. Sci.* 13:713. doi: 10.3390/bs13090713

Murayama, T., and Sekiya, H. (2015). Factors related to choking under pressure in sports and the relationships among them. *Int. J. Sport Health Sci.* 13, 1–16. doi: 10.5432/ijshs.201416

Nicholls, A. R., and Polman, R. C. (2007). Coping in sport: a systematic review. *J. Sports Sci.* 25, 11–31. doi: 10.1080/02640410600630654

Nicholls, A. R., Polman, R. C. J., Levy, A. R., and Backhouse, S. H. (2008). Mental toughness, optimism, pessimism, and coping among athletes. *Personal. Individ. Differ.* 44, 1182–1192. doi: 10.1016/j.paid.2007.11.011

Poulus, D., Coulter, T. J., Trotter, M. G., and Polman, R. (2020). Stress and coping in esports and the influence of mental toughness. *Front. Psychol.* 11:628. doi: 10.3389/fpsyg.2020.00628

Roberts, L. J., Jackson, M., and Grundy, I. H. (2019). Choking under pressure: illuminating the role of distraction and self-focus. *Int. Rev. Sport Exer. Psychol.* 12, 49–69. doi: 10.1080/1750984X.2017.1374432

Schaefer, J., Vella, S. A., Allen, M. S., and Magee, C. A. (2016). Competition Anxiety, Motivation, and Mental Toughness in Golf. *Journal of Applied Sport Psychology.* 28, 309–320. doi: 10.1080/10413200.2016.1162219

Smith, R. E., Smoll, F. L., and Schultz, R. W. (1990). Measurement and correlates of sport specific cognitive and somatic trait anxiety: the sport anxiety scale. *Anxiety Res.* 2, 263–280. doi: 10.1080/08917779008248733

Spielberger, C. D., Anton, W. D., and Bedell, J. (1976). "The nature and treatment of test anxiety" in Emotions and anxiety: New concepts, methods, and applications. eds. C. D. Zuckerman and C. D. Spielberger (New York: Erlbaum), 317–345.

Stamatis, A., Morgan, G. B., Papadakis, Z., Mougios, V., Bogdanis, G., and Spinou, A. (2021). Cross-cultural invariance of the mental toughness index among American and Greek athletes. *Curr. Psychol.* 40, 5793–5800. doi: 10.1007/s12144-019-00532-2

Tabachnick, B. G., and Fidell, L. S. (2021). Using multivariate statistics. *7th* Edn. Manhattan, NY: Harper & Row.

Thiessen, B., Sullivan, P., Gammage, K., and Dithurbide, L. (2023). Choking susceptibility and the big five personality traits. *Open Psychol. J.* 16:e187435012301130. doi: 10.2174/18743501-v16-e230116-2022-75

Wang, J. (2002). Developing and testing an integrated model of choking in sport. Doctoral dissertation. Melbourne: Victoria University.

Wang, J., Marchant, D. B., and Morris, T. (2004a). Coping style and susceptibility to choking. *J. Sport Behav.* 27, 75–92.

Wang, J., Marchant, D. B., Morris, T., and Gibbs, P. (2004b). Self-consciousness and trait anxiety as predictors of choking in sport. *J. Sci. Med. Sport* 7, 174–185. doi: 10.1016/S1440-2440(04)80007-0

Wilson, M. (2008). From processing efficiency to attentional control: a mechanistic account of the anxiety-performance relationship. *Int. Rev. Sport Exerc. Psychol.* 1, 184–201. doi: 10.1080/17509840802400787

Wilson, M., Chattington, M., Marple-Horvat, D. E., and Smith, N. C. (2007). A comparison of self-focus versus attentional explanations of choking. *J. Sport Exerc. Psychol.* 29, 439–456. doi: 10.1123/jsep.29.4.439

Woodman, T. I. M., and Hardy, L. E. W. (2003). The relative impact of cognitive anxiety and self-confidence upon sport performance: a meta-analysis. *J. Sports Sci.* 21, 443–457. doi: 10.1080/0264041031000101809

Yoon, S. J., Irie, K., Lee, J. H., and Lim, S. M. (2021). Perfectionism, mood states, and choking in Asian university baseball players under pressure during a game. *Int. J. Environ. Res. Public Health* 18:12856. doi: 10.3390/ijerph182312856

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The effects of conscious movement investment on inhibiting a simple response

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The relationship between a performer's conscious involvement or investment in movement control and monitoring and the ability to inhibit the movement is still unclear. We conducted three experiments to investigate whether a higher inclination for conscious movement investment benefits the inhibition of a simple keypress response. In all experiments, the inclination for conscious movement investment was measured with the Movement-Specific Reinvestment Scale. In Experiment 1, participants performed the go/no-go task and conscious investment was manipulated by directing conscious attention either to the finger movement (i.e., internal focus) or to the resulting motion of the key (i.e., external focus). The results showed that neither the participants' inclination for conscious movement investment, nor the direction of conscious attention affected inhibition performance. In Experiment 2, participants performed the stop-signal task, which is more attention demanding than the go/no-go task. The results showed that participants with a high or low inclination for conscious movement investment did not differ in inhibition performance. In Experiment 3 an ego-depletion procedure was included that limits resources for conscious movement investment. Before and after this ego-depletion procedure, participants performed the stop-signal task. The results showed that participants with a high inclination for conscious movement investment slowed down inhibition when they felt mentally depleted, while no slowing down of inhibition was found among participants who felt less depleted and/or had a low inclination for conscious movement investment. Together, the study provides evidence that increased conscious movement investment is beneficial for movement inhibition. Yet, these effects only emerge against the dynamic background of interacting individual (e.g., inclination for conscious movement investment, available attentional resources) and task constraints (e.g., task difficulty).

KEYWORDS

inhibition, ego-depletion, go/no-go task, stop-signal task, conscious movement investment

1 Introduction

Movements can be executed consciously or automatically. In the current study, we are interested in the conscious monitoring and control of the movement or conscious movement investment. We define conscious movement investment[1] as performer's conscious or selective attention to movement in order to monitor and/or control how it unfolds, which is accompanied by a conscious use of some degree of explicit movement-related knowledge in the ongoing movement. There is broad consensus that, for well-learned motor skills, conscious movement investment disrupts movement automaticity, leading to impaired movement performance (Wulf and Prinz, 2001; Beilock et al., 2002; Gray, 2004, 2006; Ford et al., 2005; Beilock and Gray, 2012). For example, skilled soccer players slowed down dribbling with their dominant foot when asked to consciously attend to how they touched the ball; similarly, experienced golfers showed larger aiming errors (i.e., the distance from the centre of the target) when triggered to pay attention to the follow-through motion of the clubhead (Beilock et al., 2002). Such conscious movement investment is also thought to underlie breakdown of performance in high-pressure situations (Masters, 1992). Intriguingly, however, conscious movement investment may not necessarily adversely affect the execution of movements: intentionally stopping or inhibiting movements may be facilitated by conscious movement investment (Beilock and Gray, 2012; Park et al., 2020). The purpose of the current research is to further explore this putative relationship by examining whether variations in the inclination for and/or actual degree of conscious movement investment affects inhibition.

Unlike many studies investigating how conscious movement investment affects movement outcomes, there have been only two studies so far assessing its relationship with movement inhibition (Beilock and Gray, 2012; Park et al., 2020). Beilock and Gray (2012), compared inhibition of a golf putting stroke in novices and high-skilled golfers. They assumed that novices would naturally show higher levels of conscious movement investment compared to high-skilled golfers who would show much more automatic monitoring and control of movement. This contention is based on the theory of skill acquisition (Fitts and Posner, 1967), which posits that, during the initial stage of learning, movement execution is controlled by unintegrated control structures which are held in working memory. As learning progresses, performers develop encapsulated procedural structures that allow for the automatic, nonconscious monitoring and control of movement. In the study of Beilock and Gray (2012), they asked participants to putt on an indoor green. A stop signal (i.e., an auditory tone) appeared at the backswing or downswing of strokes on some trials (i.e., 33%). Then participants were required to halt the putting stroke as quickly as possible after hearing a stop signal. They found that the novices were faster in inhibiting the stroke than the high-skilled golfers, especially when the stop signal was present during the downswing. Beilock and Gray (2012) argued that novices were faster in stopping the stroke, because they were already consciously investing (i.e., monitoring and/or controlling) to the putting movement, while high-skilled golfers first had to shift attention toward the movements (Gray, 2009; Beilock and Gray, 2012).

Recent observations by Park et al. (2020) were (partially) consistent with this result. While Beilock and Gray (2012) assumed that their participants, depending on skill level, invested different degrees of consciousness in movements, Park et al. (2020) tried to more directly pinpoint the relationship between conscious movement investment and inhibition. In fact, they reasoned that inhibition would allow performers to control the degree of conscious movement investment. They thus expected that movement inhibition would negatively correlate with performers' inclination to consciously invest in movement monitoring and control.[2] To this end, Park et al. (2020) measured participants' inclination for conscious movement investment via a questionnaire. The questionnaire, referred to as the Movement-Specific Reinvestment Scale (MSRS), was originally introduced and validated by Masters et al. (1993), see also Kal et al., 2016) to assess performers' inclination for conscious (re-)investment in high-pressure situations. The MSRS consists of 10 statements about moving in general that gauge movement self-consciousness and conscious movement processing. Previous studies using the MSRS have shown that performers with a high MSRS score more likely demonstrate high levels of investment of explicit movement-related knowledge in motor performance and learning (Malhotra et al., 2015; van Ginneken et al., 2017, 2018) and increased likelihood of performance breakdown in high-pressure situations due to de-automatisation movement monitoring and control (Maxwell et al., 2006).

Park et al. (2020) asked participants to complete the MSRS and the go/no-go task (i.e., GNG task). The GNG task is one of the classic tasks for measuring movement inhibition, requiring participants to respond to go signals (i.e., go trials) or withhold a response in response to stop signals (i.e., no-go trials or stop trials). The frequency of commission errors (i.e., the probability of executing a response on no-go trials) is the primary inhibition measure in the GNG task (Verbruggen and Logan, 2008). Park et al. (2020) did not find a correlation between the MSRS score and the frequency of commission errors. However, they did reveal a negative correlation between the MSRS score and the variability in the go reaction time. The variability in the go reaction time has been suggested to be positively correlated with the frequency of commission errors (Bezdjian et al., 2009). Hence, if anything, this observation suggests that individuals with a high inclination for conscious movement investment show better movement inhibition. This opposed Park et al.'s (2020) original expectation but is consistent with Beilock and Gray (2012) hypothesis.

1 The concept of conscious movement investment is adapted from the theory of reinvestment (Masters and Maxwell, 2008). The theory of reinvestment holds that automatized movements are disrupted if a skilled performer re-uses or re-invest task-relevant declarative or explicit movement-related knowledge to monitor and control a movement. This especially happens under stressful circumstances (Masters, 1992). With conscious movement investment, we refer to the same process of using explicit movement-related knowledge to monitor and control a movement but in a more general way, also including novice performers deliberately monitoring and controlling movements in non-stressful circumstances.

2 The reversal of causality relative to Beilock and Gray (2012) and our arguments.

The empirical evidence for a relationship between conscious movement investment and movement inhibition is still weak. Firstly, Park et al. (2020) only provided evidence for such a relationship for the variability in the go reaction time, but not for the frequency of commission errors, which is the primary index for movement inhibition for the GNG task (Verbruggen and Logan, 2008). Secondly, in the GNG task there is a consistent signal-response mapping, that is, go and no-go signals are mutually exclusive (Verbruggen and Logan, 2008). The consistent mapping between the no-go signal and no-go response allows an automatic triggering of the no-go response and requires relatively low levels of conscious attention on the task (Logan and Cowan, 1984; Verbruggen and Logan, 2008). If conscious attention to the task is low, then attention to the movement is likely low as well. Thus, the GNG task may require insufficient conscious movement investment, even for participants with a high inclination for conscious movement investment. Thirdly and relatedly, Beilock and Gray (2012) and Park et al. (2020) did not directly manipulate conscious movement investment but capitalised on individual differences in the likelihood that participants would consciously invest in the tasks. Hence, it remains unknown to what degree participants were actually consciously attending when performing the GNG task or golf task. It is therefore important to further explore the relationship between the (inclination for) conscious movement investment and movement inhibition under conditions that require varying amounts of conscious movement investment.

Accordingly, to further explore the relationship between the (inclination for) conscious movement investment and movement inhibition, three experiments were conducted. In Experiment 1, we directly manipulated conscious movement investment and investigated whether increased and reduced conscious movement investment differently affected movement inhibition as assessed by the GNG task. A common approach to manipulate conscious movement investment is to provide participants with instructions that encourage them on where to focus (Wulf, 2013). It has been shown that focusing on the movements themselves (i.e., internal focus) increases conscious investment of explicit movement-related knowledge while focusing on the effects of movements (i.e., external focus) reduces conscious movement investment (Poolton et al., 2006). Therefore, to manipulate conscious movement investment, internal and external foci of attention were utilized. We also tested to what degree the effect of conscious movement investment on inhibition was moderated by the participants' inclination for conscious movement investment as assessed by the MSRS.

In Experiment 2, rather than using the GNG task, we used the stop-signal task (SST) to assess movement inhibition. The SST requires participants to perform a choice reaction time task (CRTT) by pressing buttons in response to different go signals. The stop signal (e.g., a change in the colour of the go signal) occurs shortly after the go signal, requiring participants to withhold the response (Verbruggen and Logan, 2008). Because the stop response is preceded by a combined go and stop signal, the mapping between the stop signal and stop response is inconsistent. This inconsistency necessitates that participants continually prepare to stop, thereby requiring higher levels of conscious attention in the task compared to the GNG task (Verbruggen and Logan, 2008), presumably increasing conscious movement investment as well. Hence, in Experiment 2, we examined the relationship between the inclination for conscious movement investment, as measured with the MSRS, and movement inhibition on the SST.

Finally, in Experiment 3, we manipulated the capacity for conscious movement investment by depleting participants' resources upon which conscious movement investment depends – that is, the resources for self-control. Self-control refers to the capacity to override or alter predominant responses, and it represents a limited cognitive resource that depletes with exertion. The state that follows the depletion of self-control is referred to as ego-depletion (Baumeister et al., 2007; Hagger et al., 2010). In the SST, participants presumably invest more conscious effort in task execution compared to the GNG task, especially individuals with higher inclination for conscious movement investment. Maintaining conscious movement investment requires self-control resources as it is one form of self-control (Bruya, 2010). Thus, in Experiment 3, we manipulated the capacity for conscious movement investment using a validated dual-task paradigm for ego-depletion (Hagger et al., 2010; Pohl et al., 2013). We assessed whether reducing the capacity for conscious movement investment influenced movement inhibition as assessed by the SST. Like in Experiment 1, we also tested whether the effects, if any, were moderated by the inclination for conscious movement investment.

2 Experiment 1

A few studies have suggested that a positive association exists between conscious movement investment and movement inhibition (Beilock and Gray, 2012; Park et al., 2020). This evidence is derived from a comparison across groups of individuals, who presumably showed different degrees of conscious investment in movement monitoring and control. However, the degree of conscious movement investment was not directly manipulated in those studies. Hence, in Experiment 1, we examined the effect of various degree of conscious movement investment on inhibition in the GNG task. Additionally, following Park et al. (2020), we investigated whether the inclination for conscious movement investment moderated this effect. To increase conscious movement investment, we instructed participants to direct attention to the movement while performing the GNG task (i.e., internal focus; Wulf and Su, 2007) and compared this with their performance when instructed to focus on the effect of the movement (i.e., external focus). It is presumed that an internal focus increases conscious attention to the movement, which not only results in less fluent (or automatic) movement execution (Kal et al., 2013) but also in worse performance outcomes compared to an external focus (Wulf et al., 1998; Wulf and Prinz, 2001; Wulf and Su, 2007; Wulf, 2013).

Hence, in Experiment 1, we aimed to manipulate participants' levels of conscious movement investment in the GNG task by requiring them to perform under internal and external focus instructions and measured their inclination for conscious movement investment via the MSRS. We predicted that internal focus instructions and the concomitant increase in conscious movement investment would result in increased inhibition as reflected by a lower frequency of commission errors in comparison to external focus instructions, especially among the participants who show a strong inclination for conscious movement investment.

2.1 Materials and methods

2.1.1 Participants

A total of 41 participants (age: 31.0 ± 3.8 years old, 16 males, 25 females) from Taiwan and the Netherlands were recruited through the internet. G*power (version 3.1.9.6) showed at least 34 participants were need for detecting a within-between interaction with a power level of 80%, a moderate effect size of 0.25 at a significance level of 0.05. Participants self-reported handedness: 37 were right-handed, 3 were left-handed, and 1 was ambidexter. None of the participants reported a history of neurological or motor problems, or of having visual impairments. The study was approved by the local institution's ethics committee and participants gave informed consent before the start of the experiment.

2.1.2 Tasks and materials

2.1.2.1 MSRS

Movement-Specific Reinvestment Scale comprises of 10 items loading on 2 factors (Masters et al., 2005). Five items assess conscious movement processing, such as, "I try to figure out why my actions failed," while the other five items gauge, according to a recent interpretation, conscious movement monitoring (Malhotra et al., 2015), for example, "I am aware of the way my body works when I am carrying out a movement." Each item is rated on a 6-point Likert scale, ranging from *1 (strongly disagree) to 6 (strongly agree).* The cumulative scores range from 10 to 60, the higher the score the stronger the inclination for conscious movement investment.

2.1.2.2 GNG task

The GNG task (see Figure 1) comprised of an initial practice block of 5 trials and two test blocks of 50 trials with go and no-go trials. In each block, the ratio of go trials and no-go trials was 4:1 (Park et al., 2020). On each trial, a white cross surrounded by a white circle (i.e., the starting signal) was displayed at the centre of the screen for 500 ms indicating the beginning of the trial, which was followed with a right-pointing or left-pointing arrow displayed for 1,000 ms. On go trials, a green left-pointing or right-pointing arrow served as the go signal. Participants were asked to press the S or K key as quickly as possible after the green left-pointing or right-pointing arrow appeared on the screen, respectively. On no-go trials, a red left-pointing or right-pointing arrow served as the no-go signal and participants were instructed not to press any key if a red signal appeared. Both go signals and no-go signals remained visible until participants pressed one of the keys or after 1,000 ms had passed. To increase conscious investment in the movement, participants were required to use their left and right ring fingers instead of their index fingers as is normally required in the GNG task. On go trials, if participants had not responded within 1,000 ms or if they had pressed the wrong key within 1,000 ms, the trial was considered as an omission trial or a wrong trial, and feedback was given, stating "You should have pressed" or "Wrong key" for 1,250 ms, respectively. On no-go trials, if participants pressed any key within 1,000 ms, the trial was considered as a commission trial and feedback was provided, stating "You should not have pressed" for 1,250 ms. A black screen with a white circle frame was shown for 1,000 ms after a go or no-go signal, or the feedback disappeared.

2.1.3 Procedure

Because of the COVID-19 pandemic, the entire experiment, including the MSRS and the GNG task, was programmed on the online website PsyToolKit (Stoet, 2010, 2017). PsyToolKit has been shown to be comparable to E-prime 3.0, a widely used psychological research tool in laboratory setting (Kim et al., 2019). Besides, the official website states that the internet speed does not influence the response times (PsyToolkit, 2021). Participants were asked to use a laptop or a desktop computer and a keyboard in a quiet room. They were asked to sit comfortably in front of the screen and first completed the MSRS. Following that, they performed the GNG task in the internal focus and the external focus conditions, the order of which was counterbalanced among participants. There was short break between blocks and two conditions.

The internal and external focus conditions only differed in how the instructions were formulated. In the internal focus condition, the participants were instructed to "use the left ring finger for pressing the S key and the right ring finger for pressing the K key. In doing so, focus your attention to your *finger movement*." In the external focus condition, they were instructed to "use the left ring finger for pressing the S key and the right ring finger for pressing the K key. In doing so, focus your attention to the motion of the *key*." To reinforce conscious movement investment throughout the GNG task, a cue with the text "keep your attention on your finger movement" or "keep your attention on the key motion" showed up after the 5th, 10th, 20th, 30th, and 40th trial of two test blocks in both the internal and external focus condition.

The participants performed the GNG task after they had participated in the SST[3] to be reported in Experiment 2.

2.1.4 Data analysis

2.1.4.1 Dependent variables

The MSRS score was calculated for each participant. For the two conditions, the mean reaction time for correct go responses (i.e., Go_Correct_RT), the ratio of correct responses to all responses on go trials (i.e., Go_Correct_Rate), the ratio of commission errors to all responses on no-go trials (i.e., No-Go_Commission_Rate) and the variability in reaction time on go trials (i.e., Go RTV; the ratio of the SD to the mean reaction time) were determined. The abbreviations of dependent variables are displayed in the Appendix.

2.1.4.2 Statistical analysis

We used R Studio (Version 1.4.1106) for data pre-processing and SPSS (Version 26) for statistical analysis. To categorize participants, we applied a mean split to the MSRS score, creating two groups: high MSRS and low MSRS. Next, the Go_Correct_RT, Go_Correct_Rate, No-Go_Commission_Rate, and Go RTV were submitted to separate 2 (group: high MSRS, low MSRS) by 2 (condition: internal, external) ANOVAs with repeated measures on the last factor. The simple main effect analysis was planned to follow

3 In the pilot work, we found the SST to be a more fatiguing task and decided to run it first. However, while structuring the paper, we determined that presenting it in the current sequence was better.

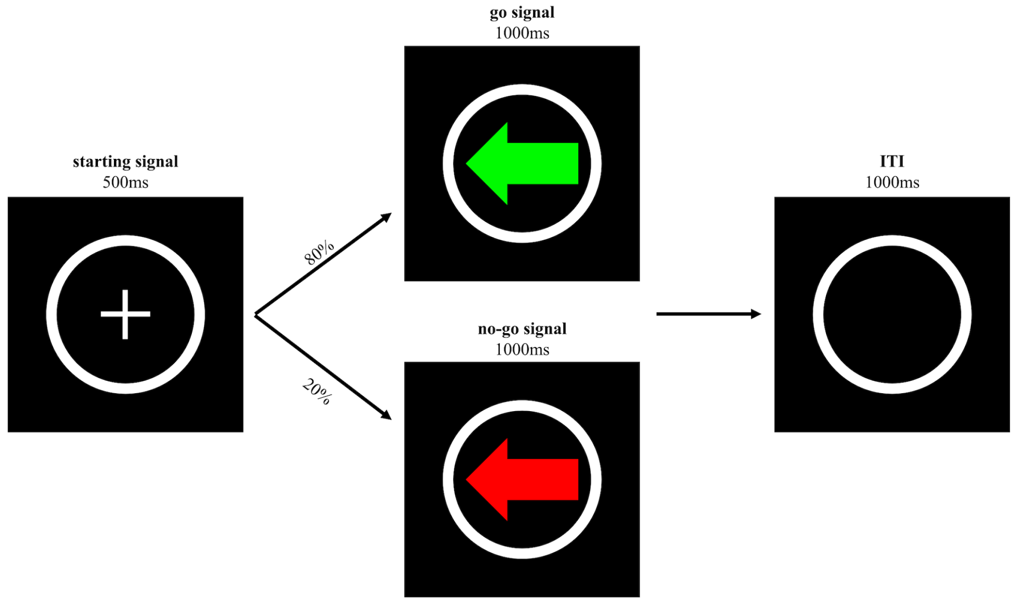

FIGURE 1
Schematic representation of the trial sequence of the GNG task. The go and no-go signal were either a left-pointing or right-pointing arrow, only the left-pointing arrow is shown here.

up significant effects. Effect sizes were calculated with partial eta-squared (i.e., η_p^2). Values of 0.01, 0.06, and 0.14 were interpreted as small, medium, and large, respectively.

2.2 Results

According to the mean MSRS score (M = 41.76, SD = 8.97), 22 participants were assigned to the high MSRS group (M = 48.45, SD = 3.66), and 19 participants to the low MSRS group (M = 34.00, SD = 6.69). Table 1 shows that no differences between groups and conditions were apparent. Accordingly, the ANOVA did not reveal significant effects for group, condition, and group by condition (Table 2).

2.3 Discussion

In Experiment 1, we investigated whether the degree of conscious movement investment affects inhibition. To manipulate conscious movement investment, participants performed the GNG task with internal and external focus instructions. We hypothesized that an internal focus of attention increases conscious movement investment and would result in enhanced inhibition performance compared to an external focus of attention, especially for participants with a high inclination for conscious movement investment.

Neither participants' inclination for conscious movement investment nor the momentary degree of conscious attention for movement execution influenced inhibition performance in the GNG task. That is, the most critical indicator, commission rate, did not differ as a function of group or focus condition. Also, the more indirect measures for inhibition performance did not show any differences (see Table 1). This included the variability in reaction time of go trials (i.e., Go RTV), which was previously reported to correlate to the MSRS score (Park et al., 2020). These findings suggest that inhibition was not influenced by the degree of conscious movement investment or the inclination to consciously invest in movement execution.

One concern with the generality of this conclusion is that our manipulation of focus of attention may have been insufficiently successful. Typically, it is found that increased attention to the movement disrupts performance, especially if they concern well-developed automatic movements, such as the current button-press movements (Wulf and Su, 2007; Kal et al., 2013). For the current experiment this would have meant decreased performance for the go response in the internal focus condition. However, the correct rate and reaction time on go trials did not differ significantly between two focus of attention instructions. This accords with Ziv and Lidor (2021), who recently reported that they failed to show a difference between internal and external focus of attention instructions on a CRTT and a Simon task. Perhaps the simple button-press movements are immune to the attentional focus manipulation and/or only demand low levels of conscious movement investment. However, this remains an assumption, as Experiment 1 did not evaluate how well the two groups followed the focus of attention instructions. Future research should address this by assessing it directly. For instance, a post-manipulation questionnaire could be an effective method (Lawrence et al., 2011). An additional alternative explanation for the observed lack of difference is that participants may have learned the mapping between no-go signal and stop response, potentially reducing any contrast in conscious movement investment across the two attentional conditions. Indeed, Verbruggen and Logan (2008) previously found that inhibition became quickly automatic in the GNG task. Hence, it is important to reconsider the relationship

TABLE 1 Descriptives of Experiment 1.

	High MSRS		Low MSRS	
	Internal	External	Internal	External
Go_Correct_RT (ms)	393.76 (37.80)	397.73 (39.58)	401.62 (34.80)	405.00 (55.62)
Go_Correct_Rate (%)	98.69 (1.42)	98.58 (2.32)	98.82 (1.89)	99.41 (0.87)
No-Go_Commission_Rate (%)	3.18 (5.47)	2.05 (4.80)	1.84 (2.99)	2.63 (4.82)
Go RTV	0.13 (0.04)	0.14 (0.05)	0.13 (0.06)	0.13 (0.04)

The number in parenthesis indicate SD.

TABLE 2 Statistics of Experiment 1.

	Group			Condition			Group x condition		
	F(1,39)	*p*	η_p^2	*F*(1,39)	*p*	η_p^2	*F*(1,39)	*p*	η_p^2
Go_Correct_RT (ms)	0.47	0.50	0.01	0.25	0.62	0.01	<0.01	0.97	<0.01
Go_Correct_Rate (%)	1.40	0.24	0.04	0.43	0.51	0.01	0.94	0.34	0.02
No-Go_Commission_Rate (%)	0.09	0.77	<0.01	0.06	0.82	<0.01	1.72	0.20	0.04
Go RTV	0.43	0.52	0.01	0.02	0.89	<0.01	0.77	0.39	0.02

between conscious movement investment and inhibition with task constraints that potentially induce higher levels of conscious movement investment.

3 Experiment 2

In Experiment 2, we investigated the purported positive relationship between conscious movement investment and movement inhibition using the SST, which is argued to require increased levels of conscious attention to the task compared to the GNG task (Verbruggen and Logan, 2008). In the SST, the mapping between a no-go or stop signal and a stop response varies, in contrast to the consistent mapping between a no-go signal and a stop response in the GNG task (Verbruggen and Logan, 2008). The inconsistent mapping in the SST means that participants continuously need to be prepared to inhibit a go response. In this sense, participants must pay greater conscious attention to the SST, which is presumably associated with greater conscious investment in movement. Another advantage of using the SST is that it provides a more quantitative measure for movement inhibition, instead of only estimating the frequency of commission errors. That is, the primary measure is the stop-signal reaction time (SSRT), indicating the time needed to halt an intended movement response. Consequently, in Experiment 2, we determined the SSRT and examined whether it differed between participants who show high and low inclinations to conscious movement investment, using the MSRS. We hypothesized that the SSRT would be shorter for participants with a high inclination for conscious movement investment compared to those with a low inclination for conscious movement investment.

3.1 Materials and methods

3.1.1 Participants

The participants were the same as the Experiment 1.

3.1.2 Tasks and materials

3.1.2.1 MSRS

See Experiment 1.

3.1.2.2 The choice reaction time task

Participants performed a CRTT (see Figure 2). The CRTT consisted of one practice block of 16 trials and 1 test block of 48 trials. On each trial, a white cross surrounded by a white circle (i.e., starting signal) was displayed at the centre of the screen for 500 ms, indicating the beginning of the trial. This was followed by a green left- or right-pointing arrow, with a 1:1 ratio, that served as the go signal and was displayed for 1,000 ms. Participants were asked to press the A key with the left index finger or the L key with the right index finger as quickly as possible, when the left- or right-pointing arrow was shown, respectively. The go signals remained on the screen until participants pressed one of the keys or when 1,000 ms had passed. On each trial, if participants did not respond within 1,000 ms or pressed the wrong key within 1,000 ms, the trial was considered an omission trial or a wrong trial, and feedback was provided stating "You should have pressed" or "Wrong key" for 1,250 and 2,000 ms, respectively. If reaction time was longer than 500 ms (on correct go trials), feedback was provided stating "Too slow" for 1,250 ms to re-emphasize being as quickly as possible. A black screen with a white circle frame was shown for 1,500 ms after the go signals or after the feedback disappeared.

3.1.2.3 SST

The SST (see Figure 3) comprised of one practice block of 20 trials and four test blocks of 60 trials. The ratio of go trials and stop trials was 4:1 in each block. The go trials in the SST were identical to the trials in the CRTT. In other words, the required response to go signals and feedback were identical. Participants were asked to respond as quickly as possible. Like the go trials, the same green left- and right-pointing arrows surrounded by a white circle were shown (with a ratio of 1:1), but with the white circle turning red on stop trials. This change in colour served as the stop signal, occurring after the go signal with varying time delays known as the stop-signal delay (SSD). The longer the SSD,

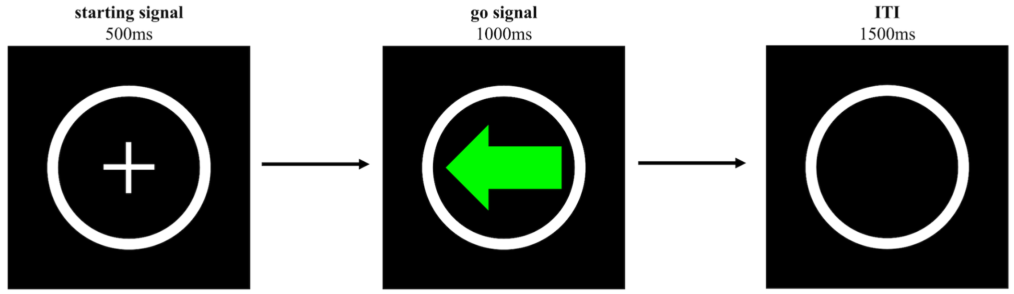

FIGURE 2
Schematic representation of the trial sequence of the CRTT. The go signal was either a green left- or right-pointing arrow. Only the left-pointing arrow is shown here.

the more difficult it is to inhibit the go response. The SSD was varied using the tracking procedure (Verbruggen et al., 2019). More specifically, when participants successfully withheld a response to a go signal, the SSD increased by 50 ms on the next stop trial; when participants failed to inhibit the go response, the SSD decreased by 50 ms on the next stop trial. The initial SSD was set 183 ms, and the minimum SSD was set 33 ms. The go and stop signals remained on the screen until participants pressed one of the keys or when 1,000 ms had passed. If participants failed to inhibit the response on stop trials, feedback was given stating "You should not have pressed" for 1,250 ms. A black screen with a white circle frame was shown for 1,500 ms after the go or stop signals or after the feedback disappeared.

3.1.3 Procedure

The experiment was done online. Participants were asked to use a laptop or a desktop computer and a keyboard in a quiet room and asked to sit comfortably in front of the screen. They first completed the MSRS. Following that, they performed the CRTT and SST in this sequence. There was short break between blocks and tasks.

3.1.4 Data analysis

3.1.4.1 Dependent variables

The MSRS score was calculated for each participant. For the CRTT, we determined the following dependent variables: the mean reaction time on all go trials (i.e., CRTT_Go_RT) and the ratio of correct responses to all responses (i.e., CRTT_Correct_Rate). For the SST, we determined the mean reaction time on all go trials (SST_Go_RT), the ratio of correct responses to all responses on go trials (i.e., SST_Go_Correct_Rate), the mean reaction time on stop trials where participants failed to stop or cancel the response (i.e., SST_Uncancelled_RT), the ratio of uncancelled responses to all responses on stop trials (i.e., SST_Uncancelled_Rate), and the mean SSD (i.e., SST_SSD). Because slowing down the go response might distort the estimation of SSRT (Band et al., 2003; Boehler et al., 2012; Verbruggen et al., 2013), response slowing was measured by subtracting the CRTT_Go_RT from the SST_Go_RT to check for the presence of distortion in each participant. Finally, and most importantly, the SSRT was estimated. The SSRT is the time interval between the onset of the stop signal and the end of the stop process. This cannot be measured directly and is therefore estimated based on the independent horse-race model (Verbruggen et al., 2019). This model assumes that movement inhibition is a race between two independent processes: the go process triggered by the go signal and the stop process triggered by the stop signal. If the go process is faster than the stop process, the response cannot be inhibited. However, if the stop process is faster than the go process, the response will be inhibited. We used the integration method to estimate the SSRT (Matzke et al., 2018). The moment at which the stop process finishes is estimated by integrating the distribution of reaction times on go trials and identifying the point at which the integral equals the SST_Uncancelled_Rate. In other words, the end of the stop process corresponds to the reaction time on go trials at the percentile that corresponds to the SST_Uncancelled_Rate (n-th RT) (i.e., including go trials with a wrong response or an omission response, where an omission response was replaced by the maximum reaction time, that is, 1,000 ms). For example, if the total number of go trials is 300, and the SST_Uncancelled_Rate is 0.45, then the n-th RT is the 135th fastest RT on Go trials (i.e., 300×0.45). SSRT is then estimated by subtracting SST_SSD from the n-th RT (i.e., SSRT = n-th RT − SST_SSD). In this study, we adopted the block-wised integration method to estimate the SSRT. Specifically, SSRT in each block was estimated solely, and then the summary SSRT was calculated by averaging the SSRTs of the four blocks (Verbruggen et al., 2013; Matzke et al., 2018). The abbreviations of dependent variables are displayed in the Appendix.

3.1.4.2 Statistical analysis

R studio (Version 1.4.1106) was used to pre-process the data, and SPSS (Version 26) was used for statistical analysis. We used a mean split for the MSRS score to assign individual participants to either the high MSRS group or the low MSRS group. Next, to reliably estimate the SSRT, several assumptions were tested based on the independent horse-race model (Logan and Cowan, 1984). First, if for an individual participant the SST_Uncancelled_RT was longer than the SST_Go_RT, then the participant was excluded because this would violate the assumption of independence of the go and stop processes that underpins the horse-race model (Verbruggen et al., 2019). However, no participants were excluded for this reason. Second, if a participant's SST_Uncancelled_Rate was higher than 85% or lower than 15%, the participant would also be excluded (Chen et al., 2009). Again, this did not apply to any participant. Finally, the independent t-tests were performed to examine differences between the high and low MSRS group. Significant levels were set at the 0.05 level. Cohen's d was calculated

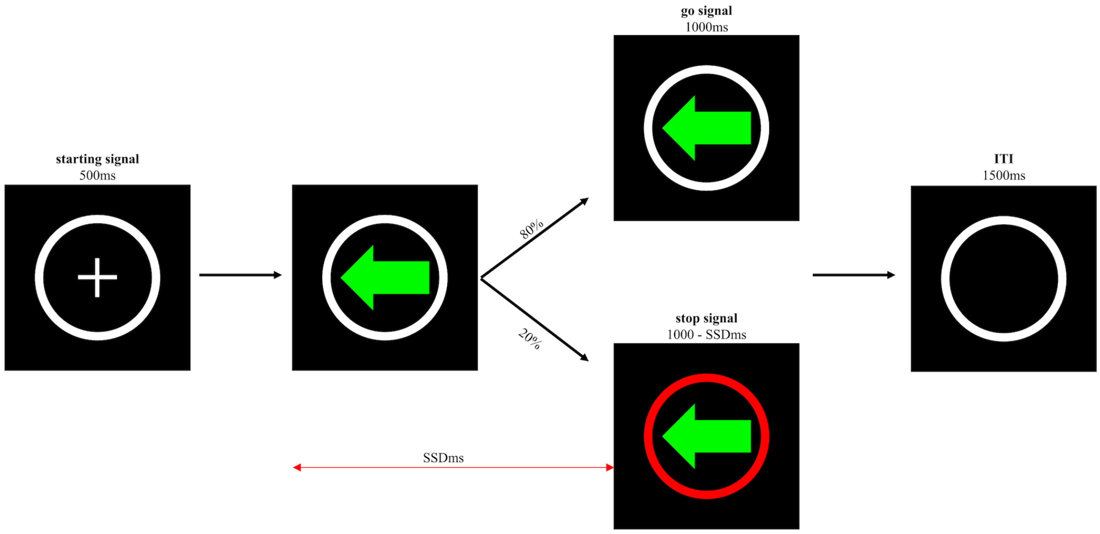

FIGURE 3
Schematic representation of the trial sequence of the SST. The go or stop signal was either a left or a right-pointing arrow. Only the left-pointing arrow is shown here.

TABLE 3 Descriptives and statistics of Experiment 2.

	High MSRS	Low MSRS	*t*(39)	*p*	*d*
SST_Go_RT (ms)	422.21 (43.21)	425.31 (26.59)	0.27	0.79	0.09
SST_Go_Correct_Rate (%)	98.32 (1.94)	99.23 (0.91)	1.88	0.07	0.59
SST_Uncancelled_Rate (%)	54.07 (5.94)	51.32 (2.22)	−1.91	0.06	−0.60
Response slowing (ms)	51.73 (27.31)	52.71 (25.26)	0.12	0.91	0.04
SSRT (ms)	277.01 (41.98)	257.92 (30.97)	−1.63	0.11	−0.51

The number in parenthesis indicate SD.

to estimate the effect size with values of 0.2, 0.5, and 0.8 considered as small, medium, and large, respectively.

3.2 Results

The assignment of participants to the high and low MSRS groups was identical as in Experiment 1. Table 3 reports the results of Experiment 2. We did not find any difference between the two groups. Importantly, there were no significant differences between the two groups in SSRT, $t(39) = -1.63$, $p = 0.11$, $d = -0.51$.

3.3 Discussion

In Experiment 2, we compared inhibition performance on the SST for participants with a high and low inclination for conscious movement investment. Unlike the GNG task used in Experiment 1, the inconsistent signal-response mapping in the SST would increase the level of conscious involvement in task, likely increasing conscious movement investment as well. We hypothesized that individuals with a high inclination for conscious movement investment would need less time to stop in response to the stop signal (i.e., SSRT) compared to individuals with a low inclination for conscious movement investment.

However, the SSRT, which is considered the main indicator for inhibition performance on the SST, did not differ between the participants with a high and low inclination for conscious movement investment. As per Experiment 1, it is possible that simple button-press movement responses may not demand a high level of conscious movement investment, even with inconsistent mapping between signal and response (Ziv and Lidor, 2021). Nonetheless, participants with a high inclination for conscious movement investment showed a nonsignificant tendency to more often forego a go response (i.e., reflecting a lower accuracy rate on go trials) and to fail to inhibit after a stop signal in comparison to participants with a low inclination for conscious movement investment (see Table 3). Possibly, the participants with high inclination for conscious movement investment might have differently traded off the requirements for a fast response and successful inhibition (Castro-Meneses et al., 2015; Schmitt et al., 2018). However, with the current smaller sample size, caution must be applied, also in interpreting the null finding for the more critical SSRT.

In sum, we found no support in the current experiment for the proposal that participants with a high propensity for conscious movement investment would show shorter inhibition times. Yet, with the small sample size, this finding needs to be reassessed. In that respect, one might anticipate that if, in addition to differences in participants' inclination for conscious movement investment, the capacity or resources for actual conscious investment in movement were manipulated, this would provide a stronger test of the putative influence of conscious movement investment on inhibition.

4 Experiment 3

In Experiment 3, we manipulated the capacity for conscious movement investment by depleting the resources for self-control. According to the self-regulation strength model, the resources for acts of self-control are limited (Baumeister et al., 2007). Due to this limited capacity, if self-control resources are depleted (i.e., the energy for mental activities is low), then self-control will be impaired in a subsequent task (Baumeister et al., 2007). Consequently, in Experiment 3, participants first performed the SST to determine baseline inhibition performance. The self-control resources of the participants were then depleted using a transcriptional task (Englert and Bertrams, 2014), after which they performed the SST again. This allowed us to test whether a reduced capacity for conscious movement investment following the ego-depletion resulted in prolonged SSRT, and whether this would be moderated by the participant's inclination for conscious movement investment. We hypothesized that participants with a high inclination for conscious movement investment would show larger increase in SSRT after depletion (i.e., in the post-intervention test compared to the baseline test) than participants with a low inclination for conscious movement investment.

4.1 Materials and methods

4.1.1 Participants

A total of 40 participants (age: 24.3 ± 3.4 years old, 16 males, 24 females) were recruited through the internet, who were mostly from Indonesia, the Netherlands, and France. They did not participate in Experiments 1 and 2. A medium-to-large effect for ego-depletion on self-control dependent variables was reported, that is, Cohen's d = 0.62 (Hagger et al., 2010). We converted, Cohen's d in f based on the equation $\frac{d}{2}$, resulting in a f of 0.31(Correll et al., 2020). G*Power (version 3.1.9.6) showed that at least 36 participants were needed to detect a three-way interaction with a power level of 80% at a significance level of 0.05. None of the participants reported a history of neurological or motor problems or visual impairments. The experiment was approved by the local institution's ethics committee and participants gave their informed consent before starting the experiment.

4.1.2 Tasks and materials

4.1.2.1 MSRS

See Experiment 1.

4.1.2.2 CRTT

The CRTT comprised of one practice block of 40 trials. However, participants could quit the practice block after having pressed the correct key in the first 20 trials. This was followed by a test block of 50 trials. On each trial, a white cross (i.e., starting signal) was displayed at the centre of the screen for 500 ms, indicating the beginning of the trial, followed by a black screen that was presented for 200 ms. Next, a white circle appeared on the left or right side of the screen for 1,000 ms. This white circle served as the go signal. Participants were instructed to press the F key with the left index finger or the J key with the right index finger as quickly and accurately as possible when the white circle appeared on the left or right side of the screen, respectively. If participants pressed the wrong key within 1,000 ms, the trial was considered a wrong trial and feedback was given stating "Wrong key." The feedback was shown for 2,000 ms. The go signal remained on the screen until participants pressed one of the keys or after 1,000 ms had passed. A black screen was shown for 1,000 ms after a go signal or the feedback had disappeared.

4.1.2.3 SST

The SST[4] procedure adopted in Experiment 3 was based on previous research (Chen et al., 2009; Wang et al., 2013) and differed from the SST used in Experiment 2. It consisted of two phases; the first phase was to measure a participant's SSD at which the uncancelled rate was around 50% (i.e., the critical SSD), the second phase was to measure a participant's SSRT. This SST procedure helped to reduce the number of trials in the second phase compared to Experiment 2 (Chen et al., 2009). The SST had identical go trials as the go trials in the CRTT; that is, a white circle appeared at the left or right side of the screen. On stop trials, a second white circle, which is the stop signal, appeared at the centre of the screen following the go signal. Participants were asked not to press any key if it appeared. Both the go and stop signal remained on the screen until participants pressed one of the keys or 1,000 ms had passed. On go trials, the trial was considered a wrong trial if participants pressed the wrong button within 1,000 ms, and feedback was given stating "Wrong key." The trial was considered an omission trial if participants did not press any button within 1,000 ms. If they pressed the correct key, but the reaction time was longer than 500 ms, feedback was given stating "Response too slowly." This was done to prevent participants from slowing down the go response. On stop trials, if participants pressed any key within 1,000 ms, the trial was considered a commission trial, and feedback was given stating "You should not have pressed." All feedback statements were shown for 2,000 ms. A black screen was displayed for 1,000 ms after a go or stop signal, or after the feedback had disappeared.

The SST consisted of two phases. *Phase 1*: In this first phase, the critical SSD was determined. It consisted of a practice block of 32 trials and several test blocks of 32 trials. The go and stop trials, with a ratio of 3:1 in each block, were presented in random order. For each participant, we manipulated the SSD across blocks to obtain the critical SSD. The SSD was set at 183 ms in the first block. If the cancelled rate was higher than 63%, the SSD increased by 50 ms in the next block; if the cancelled rate was lower than 38%, the SSD decreased by 50 ms in the next block; and if the cancelled rate was between 63% and 38%, the SSD remained the same in the next block. The first phase ended once the participant's cancelation rate was between 63% and 38% in two consecutive blocks. The SSD in these blocks was considered as the critical SSD. *Phase 2*: The second phase consisted of a practice block of 24 trials and three test blocks

4 To reduce the number of trials in the SST for both tests, we adopted a different SST procedure (Chen et al., 2009; Wang et al., 2013). This resulted in the visual stimuli and procedures for the CRTT and SST in Experiment 3 being different from those in Experiment 2.

of 48 trials. The ratio of go trials and stop trials was 3:1 in each block, and the types of trials were presented randomly. In each block, there were three different SSDs: (1) critical SSD − 50 ms; (2) critical SSD; and (3) critical SSD + 50 ms. Each SSD appeared four times in each test block in random order.

4.1.2.4 Transcriptional task

The Transcriptional Task was used to induce ego-depletion. The Transcriptional Task has been applied and validated in previous studies (Wolff et al., 2013; Englert and Bertrams, 2014). Following Englert and Bertrams (2014), participants received a neutral text ("Stalagmites and Stalactites," 2011) and were asked to copy it. Participants in the ego-depletion group (i.e., EDG) were asked to copy the text, but requested to omit letters "a" and "i" so that the word "stalagmite" would then be typed as "stlgmte" and "stalactites" would be "stlcttes." Because participants in this group needed to intentionally override the writing habits when they transcribed the text, self-control strength was expected to get depleted (Englert and Bertrams, 2014). Participants in the control group (i.e., CG) were instructed to copy the text verbatim, which did not require self-control strength. To verify (perceived) depletion, after participants had finished the Transcriptional Task, participants completed three questions on a 4-point Likert scale from *not at all* (1) to *very much* (4) (Bertrams et al., 2010). These included, "How difficult did you find the task?", "How depleted do you feel at the moment?", and "How effortful did you find the task?"). The total score was defined as the depletion scores.

4.1.3 Procedure

The experiment was done online. Figure 4 shows the design of Experiment 3. Participants were randomly assigned to either, the EDG and CG. Data collection took 2 days for each participant. On the first day, participants first completed the MSRS, and then performed the CRTT followed by phase 1 of the SST. At the second day, phase 2 of the SST was performed twice. After, the first or baseline test was completed, they performed the Transcriptional Task and then performed phase 2 of the SST again, the second or post-intervention test. After each block and task, participants were granted a short break, however, they were asked to perform the post-intervention test immediately after they had completed the Transcriptional Task (i.e., without a break).

4.1.4 Data analysis

4.1.4.1 Dependent variables

The total score of the MSRS was calculated (i.e., MSRS score). For the CRTT, we measured the CRTT_Go_RT. For the SST, SST_Go_RT, SST_Go_Correct_Rate, SST_Uncancelled_RT, SST_Uncancelled_Rate, and most importantly, the SSRT were measured separately for the baseline and post-intervention test. The abbreviations of dependent variables are displayed in the Appendix. The SSRT for each of three SSDs was calculated using the integration method (including go trials with a wrong response or an omission response, where an omission response was replaced by the maximum reaction time, that is, 1,000 ms) and then averaged to obtain the mean SSRT (Wang et al., 2013). For the calculation of the SSRT of each SSD, SST_Uncancelled_Rates of 0 and 1 were replaced by 0.08 (1/12) or 0.92 (11/12), respectively, because the SSRT cannot be calculated for SST_Uncancelled_Rates of 0 or 1. For the Transcriptional Task, we counted the number of transcribed words and the number of mistakes in addition to the depletion scores.

4.1.4.2 Statistical analysis

R studio (Version 1.4.1106) was used to pre-process the data and SPSS (Version 26) was used for statistical analysis. A mean split was used for MSRS score to create a high and low MSRS group. In addition, initial perusal of the data showed large individual differences in the (perceived) depletion scores, also within the two intervention groups. Not all participants of the EDG were depleted, while participants in the CG were not always nondepleted. Because our interest is in the effects of the actual level of depletion (rather than whether or not participants had undergone the ego-depletion treatment), we also used mean split on the depletion scores to create a high and a low ego-depletion group (i.e., high and low ED group). Next, the SST_Uncancelled_RT and SST_Go_RT in both the baseline test and post-intervention test were compared for each participant. If the SST_Uncancelled_RT was longer than the SST_Go_RT in either the baseline test or post-intervention test, then the independence assumptions of the horse-race model were violated, and the participant would be excluded. No participant, however, was excluded for this reason. In addition, if a participant's SST_Uncancelled_Rate was outside 15% and 85% range they would have been excluded as well from further analyses (Chen et al., 2009). Yet, this did not apply to any participant either. However, one participant in the CG was excluded because of very low SST_Go_Correct_Rate (i.e., 55.6%).

The number of transcribed words, the number of mistakes and the depletion scores of the high and low ED groups were compared using the independent *t*-tests. Next, the SST_Go_RT, SST_Go_Correct_Rate, SSRT, and SST_Uncancelled_Rate were submitted to a separate 2 (MSRS group: high MSRS, low MSRS) by 2 (ego-depletion group: high ED, low ED) by 2 (test: baseline, post-intervention) ANOVAs with repeated measures on the last factor. The simple main effect analysis was used to follow up significant effects. Because slowing down the go response might distort the estimation of SSRT (Band et al., 2003; Boehler et al., 2012; Verbruggen et al., 2013), the response slowing was measured by subtracting the CRTT_Go_RT from the SST_Go_RT. Specifically, if a significant three-way interaction on SSRT were to be revealed, response slowing would be submitted to a similar three-way ANOVA. Partial eta-squared (η_p^2) was calculated for ANOVA to estimate the effect size with values of 0.01, 0.06, and 0.14 considered as small, medium, and large, respectively. Cohen's *d* was calculated for the independent *t*-test to estimate the effect size with values of 0.2, 0.5, and 0.8 considered as small, medium, and large, respectively.

4.2 Results

4.2.1 Group assignment

According to the mean depletion scores ($M = 7$), 19 participants were assigned to the high ED group ($M = 8.90$, SD = 0.94) and 20 participants were assigned to the low ED group ($M = 5.75$, SD = 1.07). Table 4 shows that the high ED group had significant lower number of transcribed words compared to the low ED group,

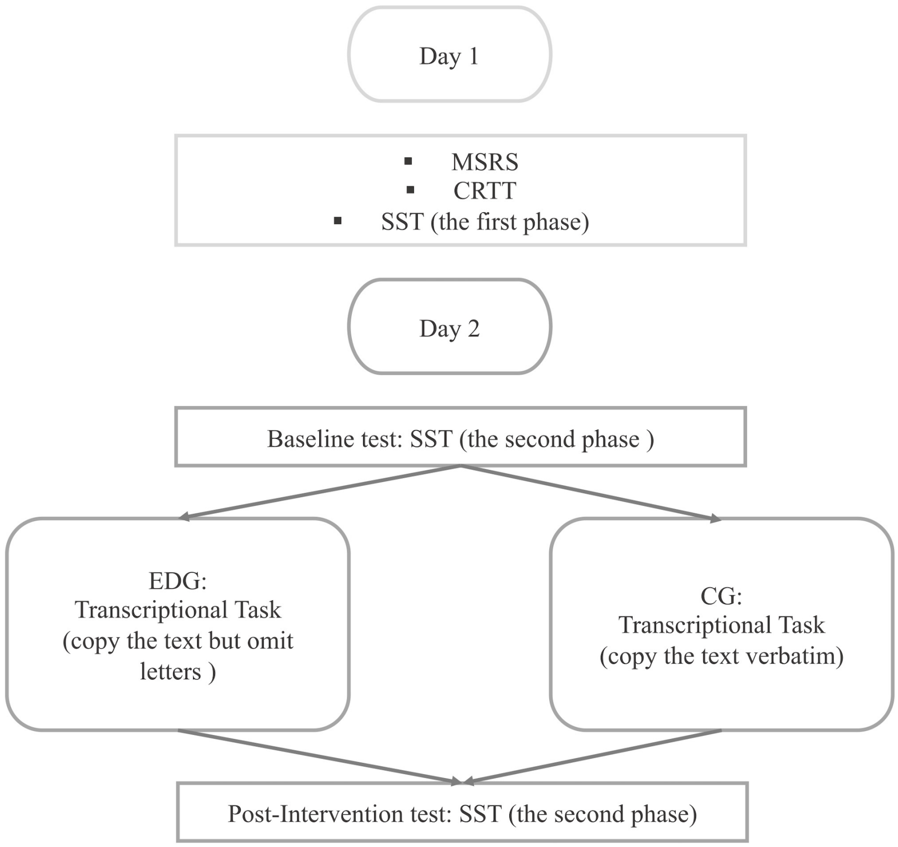

FIGURE 4
The design of Experiment 3.

TABLE 4 Descriptives and statistics of the transcriptional task in Experiment 3.

	High ED	Low ED	*t*(37)	*p*	*d*
The number of transcribed words	566.68 (16.40)	576.95 (9.42)	2.41	**0.02**	0.77
Depletion scores	8.90 (0.94)	5.75 (1.07)	−9.75	<**0.001**	−3.12
The number of mistakes	4.32 (8.29)	3.75 (11.91)	−0.17	0.87	−0.06

The number in parenthesis indicates SD. Number in bold refers to $p < 0.05$.

TABLE 5 Statistics of the stop trials in Experiment 3.

	SSRT			SST_Uncancelled_Rate		
	$F(1,35)$	p	η_p^2	$F(1,35)$	p	η_p^2
Test	0.28	0.60	0.01	0.66	0.42	0.02
Ego-depletion group	2.27	0.14	0.06	0.03	0.88	<0.01
MSRS group	0.54	0.47	0.02	0.10	0.75	<0.01
Test × ego-depletion group	0.45	0.51	0.01	0.81	0.37	0.02
Test × MSRS group	2.32	0.14	0.06	6.98	**0.01**	0.17
Ego-depletion group × MSRS group	0.89	0.35	0.03	4.16	**0.05**	0.11
Test × ego-depletion group × MSRS group	4.71	**0.04**	0.12	1.09	0.30	0.03

Number in bold refers to $p < 0.05$.

$t(37) = 2.41$, $p = 0.02$, $d = 0.77$, and the depletion scores were significantly higher for the high ED group compared to the low ED group, $t(37) = -9.75$, $p < 0.001$, $d = -3.12$. However, no significant difference between the two groups was found on the number of mistakes. According to the mean MSRS score ($M = 42.77$, SD = 8.53), 20 participants were assigned to the high MSRS group ($M = 49.40$, SD = 4.48) and 19 participants were assigned to the low MSRS group ($M = 35.79$, SD = 5.66).

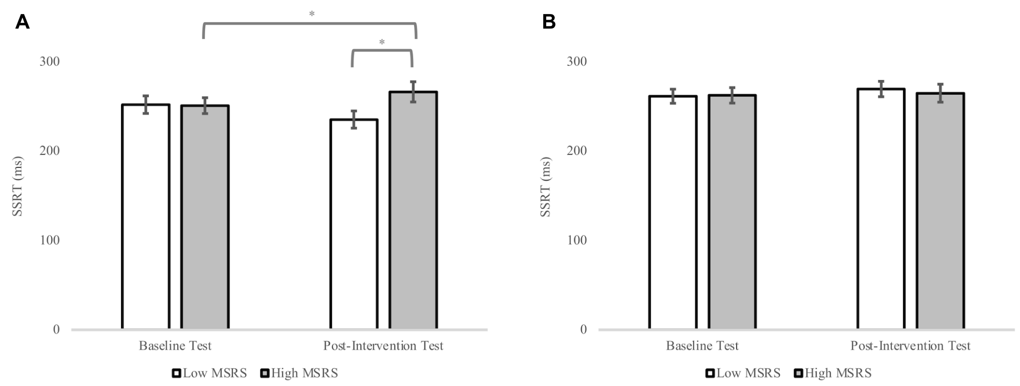

FIGURE 5
The SSRT in the SST for the low and high MSRS groups with high and low ego-depletion in the baseline and post-intervention test. **(A)** SSRT for the high and low MSRS group with high ego-depletion in the baseline and post-intervention test; **(B)** SSRT for the high and low MSRS group with low ego-depletion in the baseline and post-intervention test. Error bar represents the SEM. *$p < 0.05$.

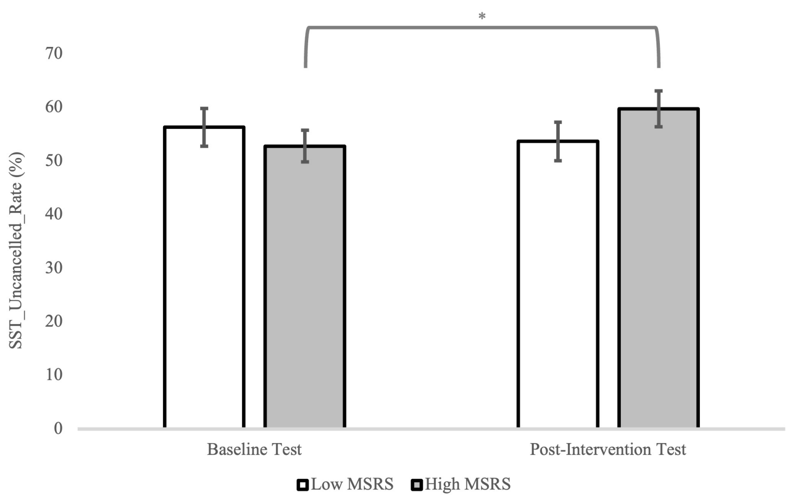

FIGURE 6
The SST_Uncancelled_Rate in the SST for the low and high MSRS groups in the baseline and post-intervention test. Error bar represents the SEM. *$p < 0.05$.

4.2.2 SST

There were no significant main effects nor any significant two-way interactions with SSRT (Table 5). However, a significant MSRS group by ego-depletion group by test interaction was found, $F(1,35) = 4.71$, $p = 0.04$, $\eta_p^2 = 0.12$. The simple main effect analyses indicated that the high MSRS group with high ego-depletion showed longer SSRT in the post-intervention test compared to the baseline test, $p = 0.05$ (Figure 5A). By contrast, the low MSRS group with high depletion scores did not show a significant difference between the two tests, $p > 0.05$. Additionally, neither the high MSRS group nor the low MSRS group with low depletion scores showed significant differences between baseline and post-intervention tests (Figure 5B), both $ps > 0.05$. The simple main effect analysis also revealed that in the post-intervention test the high MSRS group with high ego-depletion showed longer SSRT compared to the low MSRS group with high ego-depletion, $p = 0.05$ (Figure 5A). However, no difference in SSRT between the high and low MSRS group with high depletion scores in the baseline test was found, $p > 0.05$. Furthermore, no difference in SSRT between high and low MSRS group with low depletion scores in the baseline or post-intervention test was found, both $ps > 0.05$.

The ANOVA for SST_Uncancelled_Rate showed a significant MSRS group by test interaction, $F(1,35) = 6.98$, $p = 0.01$, $\eta_p^2 = 0.17$. The simple main effect analyses indicated that for the high MSRS group the SST_Uncancelled_Rate was higher in the post-intervention test compared to the baseline test, $p = 0.02$, while for the low MSRS group no difference between the two tests was found, $p = 0.21$ (Figure 6). In addition, a significant MSRS group by ego-depletion group interaction was found, $F(1,35) = 4.16$, $p = 0.05$, $\eta_p^2 = 0.11$. However, the simple main effect analyses did not identify significant differences (Figure 7).

For SST_Go_RT, SST_Go_Correct_Rate and response slowing, no main effects, two-way interactions and three-way interactions were found after performing three-way ANOVAs (Table 6), Table 7 displays the descriptives results.

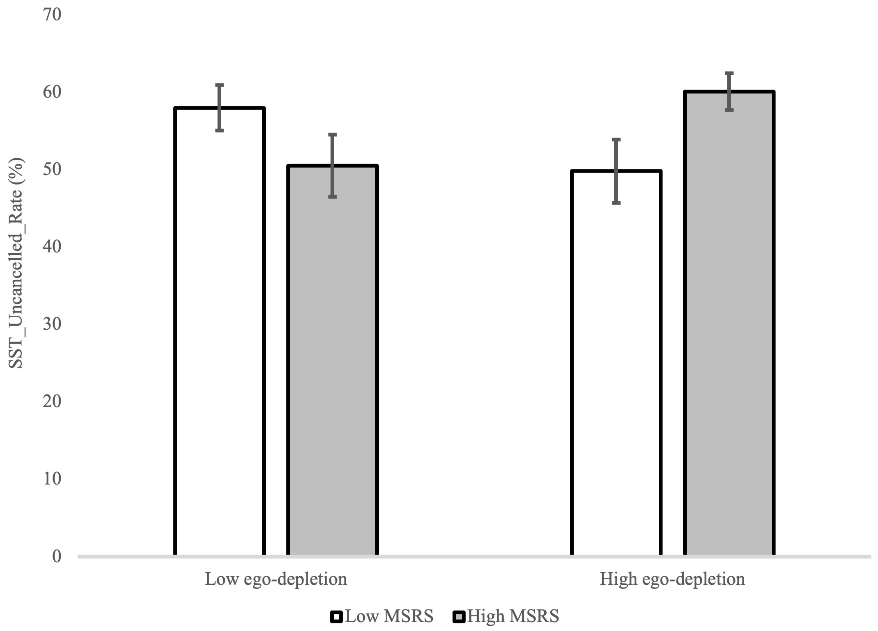

FIGURE 7
The SST_Uncancelled_Rate in the SST for the low and high MSRS groups and low and high ego-depletion group. Error bar represents the SEM.

TABLE 6 Statistics of the go trials in Experiment 3.

	SST_Go_RT			SST_Go_Correct_Rate			Response slowing		
	$F(1,35)$	p	η_p^2	$F(1,35)$	p	η_p^2	$F(1,35)$	p	η_p^2
Test	0.45	0.51	0.01	0.40	0.53	0.01	0.45	0.51	0.01
Ego-depletion group	1.77	0.19	0.05	2.22	0.15	0.06	0.68	0.42	0.02
MSRS group	3.62	0.07	0.09	0.35	0.56	0.01	2.91	0.10	0.08
Test × ego-depletion group	0.06	0.82	<0.01	2.39	0.13	0.06	0.06	0.82	<0.01
Test × MSRS group	0.29	0.59	0.01	0.24	0.63	0.01	0.29	0.59	0.01
Ego-depletion group × MSRS group	0.08	0.78	<0.01	0.93	0.34	0.03	1.81	0.19	0.05
Test × ego-depletion group × MSRS group	0.32	0.58	0.01	<0.01	0.97	<0.01	0.32	0.58	0.01

TABLE 7 Descriptives of the go trials in Experiment 3.

	High MSRS				Low MSRS			
	High ED		Low ED		High ED		Low ED	
	Baseline	Post-intervention	Baseline	Post-intervention	Baseline	Post-intervention	Baseline	Post-intervention
SST_Go_RT (ms)	403.68 (33.06)	401.91 (37.04)	388.43 (32.67)	379.95 (33.60)	422.63 (58.39)	420.69 (33.37)	409.03 (35.57)	409.86 (36.35)
SST_Go_Correct _Rate (%)	98.15 (4.20)	98.84 (1.63)	99.31 (0.96)	98.73 (1.39)	96.43 (7.47)	97.49 (4.80)	99.46 (0.62)	99.31 (1.13)
Response slowing (ms)	68.99 (66.08)	67.23 (71.02)	81.85 (35.31)	73.37 (42.53)	124.75 (63.90)	122.82 (35.42)	83.74 (55.72)	84.58 (56.38)

The number in parenthesis indicates SD.

4.3 Discussion

In Experiment 3, we tested whether reducing the capacity for conscious movement investment using an ego-depletion procedure impaired movement inhibition, and whether such effect would be enlarged for participants with a strong inclination for conscious movement investment. We anticipated that a decreased capacity for conscious movement investment due to ego-depletion would slow down inhibition (i.e., increase SSRT), and especially among participants who have a higher inclination for conscious movement investment. Indeed, we found that, for participants who felt highly depleted, the SSRT was longer for those with a high MSRS score than for those with a low MSRS score in the post-intervention test. This difference occurred because highly depleted participants with a high MSRS score prolonged their SSRT after the ego-depletion procedure, while highly depleted participants with a low MSRS score did not show a significant change in SSRT. This aligns with our hypothesis that a decreased capacity for conscious movement investment can impair movement inhibition, but only in participants who have a high inclination for conscious movement investment. This is consistent with previous observations that suggest a positive relationship between the degree of conscious movement investment and movement inhibition (Beilock and Gray, 2012; Park et al., 2020).

In addition, we found that individuals with a relatively high inclination for conscious movement investment showed a higher uncancelled rate in the post-intervention test in comparison to the baseline test (cf. Experiment 2). This increase in failing to inhibit movement, however, was present irrespective of the feeling of depletion. Since prior studies have shown that the speed of the go process might affect the estimation of SSRT (Band et al., 2003; Boehler et al., 2012; Verbruggen et al., 2013), it might be argued that the higher uncancelled rate and longer SSRT in the post-intervention test for participants with a high inclination for conscious movement investment (and who feel highly depleted) may be attributed to participants being more strongly biased towards fast responding over successful stopping compared to the baseline test. However, we did not find any indication for response slowing (Table 6), suggesting that the longer SSRT in the post-intervention test compared to the baseline test for individuals with a high MSRS score and high depletion scores was not because of the strategy that they used (i.e., a different trade off) in two tests.

Together, these findings indicate that a purported decrease in capacity for conscious movement investment after the ego-depletion procedure can deteriorate the ability for movement inhibition, particularly in participants that are predisposed to consciously invest in movement performance.

5 General discussion

There is a strong consensus that conscious involvement in well-developed motor skills normally impairs motor performance (Beilock et al., 2002; Chell et al., 2003; Jackson et al., 2006, 2013). By contrast, Beilock and Gray (2012) and Park et al. (2020) signalled that conscious attention to movement may enhance movement inhibition, instead of disrupting it. They reported that individuals who likely have high degrees of conscious movement investment (i.e., because they are less skilled or have a high predisposition for conscious movement investment) showed better ability to stop than individuals with low degrees of conscious movement investment. However, the evidence presented remained circumstantial, because it was deduced from (purported) individual or group differences in conscious movement investment rather than its direct manipulation. Hence, the present study further examined the relationship between conscious movement investment and movement inhibition, not only by exploring (purported) differences in individuals' conscious movement investment (Experiment 2), but also by comparing movement inhibition under conditions with distinct constraints on conscious movement investment (Experiments 1 and 3). Two hypotheses were formulated based on prior studies: (1) when constraints are imposed that alter conscious movement investment (i.e., by directing attentional focus away from the movement, Experiment 1) or the capability to consciously invest the movement (i.e., by limiting the available resources for conscious movement investment via ego-depletion, Experiment 3) then inhibition would be degraded; and (2) these effects would be more pronounced for individuals with a high inclination for conscious movement investment.

The two hypotheses were substantiated, but only in Experiment 3. Participants with a high propensity for conscious movement investment needed more time to stop their response when they felt mentally depleted, while no slowing down of inhibition was found among participants that felt less depleted and/or had a low inclination for conscious movement investment. This indicates that conscious movement investment can affect inhibition but only under a particular set of interacting constraints, as per Experiment 3. These conditions were seemingly not met in Experiments 1 and 2. The findings align with previous observations (Beilock and Gray, 2012; Park et al., 2020) and strengthen but nuance previous interpretations. In none of the three experiments did a direct comparison between individuals with (purported) high and low degrees of conscious movement investment reveal differences in movement inhibition, except when the task was demanding relative to available resources. In other words, neither the GNG task, even if attention was explicitly directed to the movement, nor the more difficult SST of themselves required sufficient conscious movement investment to affect inhibition. Only, when also the capacity for conscious movement investment was reduced, by depleting resources for self-control, inhibition slowed down. In other words, the degree of conscious movement investment can help to stop fast, but the effect only emerges from the dynamic interaction of individual (e.g., skill level, inclination for conscious movement investment, current resources for conscious movement investment) and task constraints (e.g., difficulty of the task).

In this respect, it is to be expected that more complex movement tasks with a higher number of degrees of freedom than the current button-press movement may show a more pronounced relationship between (the inclination for) conscious movement investment and movement inhibition, as was the case in Beilock and Gray (2012) golf putting task. Hervault et al. (2021) proposed that the time to stop or inhibit scales with the number of separate degrees of freedom to be controlled. Thus, future studies should consider using more complex movement tasks involving higher number of degrees of freedom.[5] In fact, in a follow-up study,

5 The present button-press tasks were chosen because they allowed us to continue experimental investigations during COVID-19 lock downs. Consequently, participants participated from home. The resulting impoverished interactions between experimenter and participants may have unknown effects on participants' task performance.

the present authors explored the relationship between (the inclination for) conscious movement investment and the inhibition of a golf putting stroke (You et al., 2024). This showed a relationship between conscious movement investment and stopping the golf stroke, but also suggested that this relationship is perhaps indirect via a change in movement kinematics.

Next to increasing the theoretical understanding of the relationship between conscious movement investment and motor inhibition, uncovering the constraints that affect inhibition is also of practical importance, for instance in sports performance. Athletes in open skilled sports, such as table tennis and baseball, often need to stop or adjust their planned movements to a constantly changing environment. Especially with severe time constraints, fast inhibition may bolster sport performance. There is an increasing amount of studies addressing how different degrees of conscious investment during practice or in preparation of the match shapes motor control and performance in competition and under pressure (e.g., Masters, 1992; Masters and Maxwell, 2008). This has led to proposals to preferably rely on training methods that reduce conscious investment. Yet, it is unclear whether these findings generalize to stopping or adjusting of movements. Clearly, it is of high practical relevance to shed further light on these issues.

Although the current study provides additional insights compared to previous studies, it is important to acknowledge some limitations. First, although we also manipulated the demand for conscious movement investment, and thus did not fully rely on presumed interindividual differences in conscious movement investment, it remains imperative for providing more direct evidence that subsequent research finds ways to gauge participants' actual levels of conscious movement investment, such as using verbal knowledge protocols to measure the amount of explicit movement-knowledge accumulated. Second, all three studies were conducted online because of the restrictions associated with the COVID-19 pandemic. While online research allowed researchers to continue their work during the pandemic, Finley and Penningroth (2015) argued that online research is less-controlled compared to laboratory-based research. Thus, replicating the findings in more controlled laboratory setting is important.

6 Conclusion

To conclude, the present research provides some evidence that increased conscious movement investment is associated with enhanced inhibition, and thus that conscious investment in movement is not generally debilitative. However, we also show that the effects of conscious investment in movement always emerge from the interaction with other constraints, such as, task difficulty, skill level, the inclination for conscious investment and the available 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 the Scientific and Ethical Review Board (VCWE) of the Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam. 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

YY: Conceptualisation, Data curation, Formal analysis, Methodology, Software, Supervision, Validation, Visualisation, Writing – original draft, Writing – review & editing. W-CW: Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Visualisation, Writing – original draft, Writing – review & editing. GS: Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Visualisation, Writing – original draft, Writing – review & editing. JK: Conceptualisation, Project administration, Supervision, Writing – original draft, Writing – review & editing.

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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.

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References

Band, G. P. H., van der Molen, M. W., and Logan, G. D. (2003). Horse-race model simulations of the stop-signal procedure. *Acta Psychol.* 112, 105–142. doi: 10.1016/S0001-6918(02)00079-3

Baumeister, R. F., Vohs, K. D., and Tice, D. M. (2007). The strength model of self-control. *Curr. Dir. Psychol. Sci.* 16, 351–355.

Beilock, S. L., and Gray, R. (2012). From attentional control to attentional spillover: A skill-level investigation of attention, movement, and performance outcomes. *Hum. Mov. Sci.* 31, 1473–1499. doi: 10.1016/j.humov.2012.02.014

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. doi: 10.1037//1076-898x.8.1.6

Bertrams, A., Englert, C., and Dickhäuser, O. (2010). Self-control strength in the relation between trait test anxiety and state anxiety. *J. Res. Pers.* 44, 738–741.

Bezdjian, S., Baker, L. A., Lozano, D. I., and Raine, A. (2009). Assessing inattention and impulsivity in children during the Go/NoGo task. *Br. J. Dev. Psychol.* 27, 365–383.

Boehler, C. N., Appelbaum, L. G., Krebs, R. M., Hopf, J. M., and Woldorff, M. G. (2012). The influence of different Stop-signal response time estimation procedures on behavior-behavior and brain-behavior correlations. *Behav. Brain Res.* 229, 123–130. doi: 10.1016/j.bbr.2012.01.003

Bruya, B. (2010). *Effortless attention: A new perspective in the cognitive science of attention and action*. Cambridge, MA: MIT Press.

Castro-Meneses, L. J., Johnson, B. W., and Sowman, P. F. (2015). The effects of impulsivity and proactive inhibition on reactive inhibition and the go process: Insights from vocal and manual stop signal tasks. *Front. Hum. Neurosci.* 9:529. doi: 10.3389/fnhum.2015.00529

Chell, B. J., Graydon, J. K., Crowley, P. L., and Child, M. (2003). Manipulated stress and dispositional reinvestment in a wall-volley task: An investigation into controlled processing. *Percept. Motor Skills* 97, 435–448. doi: 10.2466/pms.2003.97.2.435

Chen, C. Y., Muggleton, N. G., Tzeng, O. J., Hung, D. L., and Juan, C. H. (2009). Control of prepotent responses by the superior medial frontal cortex. *Neuroimage* 44, 537–545. doi: 10.1016/j.neuroimage.2008.09.005

Correll, J., Mellinger, C., McClelland, G. H., and Judd, C. M. (2020). Avoid Cohen's 'small','medium', and 'large'for power analysis. *Trends Cogn. Sci.* 24, 200–207. doi: 10.1016/j.tics.2019.12.009

Englert, C., and Bertrams, A. (2014). The effect of ego depletion on sprint start reaction time. *J. Sport Exerc. Psychol.* 36, 506–515. doi: 10.1123/jsep.2014-0029

Finley, A., and Penningroth, S. (2015). Online versus in-lab: Pros and cons of an online prospective memory experiment. *Adv. Psychol. Res.* 113, 135–161.

Fitts, P. M., and Posner, M. I. (1967). *Human performance*. Pacific Grove, CA: Brooks/Cole Publishing Company.

Ford, P., Hodges, N. J., and Williams, A. M. (2005). Online attentional-focus manipulations in a soccer-dribbling task: Implications for the proceduralization of motor skills. *J. Motor Behav.* 37, 386–394. doi: 10.3200/JMBR.37.5.386-394

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

Gray, R. (2006). "Expertise differences in attentional control between and within baseball batters," in *Proceedings of the human factors and ergonomics society annual meeting*, (San Francisco, CA). doi: 10.1177/154193120605001629

Gray, R. (2009). A model of motor inhibition for a complex skill: Baseball batting. *J. Exp. Psychol. Appl.* 15:91. doi: 10.1037/a0015591

Hagger, M. S., Wood, C., Stiff, C., and Chatzisarantis, N. L. (2010). Ego depletion and the strength model of self-control: A meta-analysis. *Psychol. Bull.* 136:495.

Hervault, M., Huys, R., Buisson, J.-C., Francheteau, M., Siguier, P., and Zanone, P.-G. (2021). To start or stop an action depends on which movement we perform: An appraisal of the horse–race model. *Acta Psychol.* 217:103332.

Jackson, R. C., Ashford, K. J., and Norsworthy, G. (2006). Attentional focus, dispositional reinvestment, and skilled motor performance under pressure. *J. Sport Exerc. Psychol.* 28, 49–68.

Jackson, R. C., Kinrade, N. P., Hicks, T., and Wills, R. (2013). Individual propensity for reinvestment: Field-based evidence for the predictive validity of three scales. *Int. J. Sport Psychol.* 44, 331–350.

Kal, E., Houdijk, H., Van Der Wurff, P., Groet, E., Van Bennekom, C., Scherder, E., et al. (2016). The inclination for conscious motor control after stroke: Validating the movement-specific reinvestment scale for use in inpatient stroke patients. *Disabil. Rehabil.* 38, 1097–1106. doi: 10.3109/09638288.2015.1091858

Kal, E., Van der Kamp, J., and Houdijk, H. (2013). External attentional focus enhances movement automatization: A comprehensive test of the constrained action hypothesis. *Hum. Mov. Sci.* 32, 527–539. doi: 10.1016/j.humov.2013.04.001

Kim, J., Gabriel, U., and Gygax, P. (2019). Testing the effectiveness of the Internet-based instrument PsyToolkit: A comparison between web-based (PsyToolkit) and lab-based (E-Prime 3.0) measurements of response choice and response time in a complex psycholinguistic task. *PLoS One* 14:e0221802. doi: 10.1371/journal.pone.0221802

Lawrence, G. P., Gottwald, V. M., Hardy, J., and Khan, M. A. (2011). Internal and external focus of attention in a novice form sport. *Res. Q. Exerc. Sport* 82, 431–441. doi: 10.1080/02701367.2011.10599775

Logan, G. D., and Cowan, W. B. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychol. Rev.* 91:295. doi: 10.1037/a0035230

Malhotra, N., Poolton, J. M., Wilson, M. R., Omuro, S., and Masters, R. S. W. (2015). Dimensions of movement specific reinvestment in practice of a golf putting task. *Psychol. Sport Exerc.* 18, 1–8. doi: 10.1016/j.psychsport.2014.11.008

Masters, R. S. (1992). Knowledge, knerves and know-how: The role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *Br. J. Psychol.* 83, 343–358. doi: 10.1016/j.concog.2007.03.009

Masters, R. S., and Maxwell, J. (2008). The theory of reinvestment. *Int. Rev. Sport Exerc. Psychol.* 1, 160–183.

Masters, R. S., Eves, F., and Maxwell, J. (2005). "Development of a movement specific reinvestment scale," in *Proceedings of the international society of sport psychology (ISSP) world congress*, (Sydney).

Masters, R. S., Polman, R. C. J., and Hammond, N. V. (1993). 'Reinvestment': A dimension of personality implicated in skill breakdown under pressure. *Pers. Individ. Differ.* 14, 655–666.

Matzke, D., Verbruggen, F., and Logan, G. D. (2018). The stop-signal paradigm. *Stevens Handb. Exp. Psychol. Cogn. Neurosci.* 5, 1–45.

Maxwell, J. P., Masters, R. S., and Poolton, J. M. (2006). Performance breakdown in sport: The roles of reinvestment and verbal knowledge. *Res. Q. Exerc. Sport* 77, 271–276. doi: 10.1080/02701367.2006.10599360

Park, S., Lam, W., Hoskens, M., Uiga, L., Cooke, A., and Masters, R. (2020). Inhibitory control, conscious processing of movement and anxiety. *Psychol. Sport Exerc.* 46:101587. doi: 10.1111/j.1471-4159.2007.04454.x

Pohl, R. F., Erdfelder, E., Hilbig, B. E., Liebke, L., and Stahlberg, D. (2013). Effort reduction after self-control depletion: The role of cognitive resources in use of simple heuristics. *J. Cogn. Psychol.* 25, 267–276.

Poolton, J. M., Maxwell, J. P., Masters, R. S., and Raab, M. (2006). Benefits of an external focus of attention: Common coding or conscious processing? *J. Sports Sci.* 24, 89–99. doi: 10.1080/02640410500130854

PsyToolkit (2021). *Frequently asked questions*. Available online at: https://www.psytoolkit.org/faq.html (accessed May 1, 2024).

Schmitt, L. M., White, S. P., Cook, E. H., Sweeney, J. A., and Mosconi, M. W. (2018). Cognitive mechanisms of inhibitory control deficits in autism spectrum disorder. *J. Child Psychol. Psychiatry* 59, 586–595.

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). PsyToolkit: A novel web-based method for running online questionnaires and reaction-time experiments. *Teach. Psychol.* 44, 24–31.

van Ginneken, W. F., Poolton, J. M., Capio, C. M., van der Kamp, J., Choi, C. S., and Masters, R. S. (2018). Conscious control is associated with freezing of mechanical degrees of freedom during motor learning. *J. Motor Behav.* 50, 436–456. doi: 10.1080/00222895.2017.1365045

van Ginneken, W. F., Poolton, J. M., Masters, R. S., Capio, C. M., Kal, E. C., and van der Kamp, J. (2017). Comparing the effects of conscious monitoring and conscious control on motor performance. *Psychol. Sport Exerc.* 30, 145–152.

Verbruggen, F., and Logan, G. D. (2008). Automatic and controlled response inhibition: Associative learning in the Go/No-Go and stop-signal paradigms. *J. Exp. Psychol. Gen.* 137, 649–672. doi: 10.1037/a0013170

Verbruggen, F., Aron, A. R., Band, G. P., Beste, C., Bissett, P. G., Brockett, A. T., et al. (2019). A consensus guide to capturing the ability to inhibit actions and impulsive behaviors in the stop-signal task. *Elife* 8:e46323. doi: 10.7554/eLife.46323

Verbruggen, F., Chambers, C. D., and Logan, G. D. (2013). Fictitious inhibitory differences: How skewness and slowing distort the estimation of stopping latencies. *Psychol. Sci.* 24, 352–362. doi: 10.1177/0956797612457390

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

Wolff, W., Baumgarten, F., and Brand, R. (2013). Reduced self-control leads to disregard of an unfamiliar behavioral option: An experimental approach to the study of neuroenhancement. *Subst. Abuse Treat. Prev. Policy* 8, 1–6. doi: 10.1186/1747-597X-8-41

Wulf, G. (2013). Attentional focus and motor learning: A review of 15 years. *Int. Rev. Sport Exerc. Psychol.* 6, 77–104.

Wulf, G., and Prinz, W. (2001). Directing attention to movement effects enhances learning: A review. *Psychono. Bull. Rev.* 8, 648–660.

Wulf, G., and Su, J. (2007). An external focus of attention enhances golf shot accuracy in beginners and experts. *Res. Q. Exerc. Sport* 78, 384–389. doi: 10.1080/02701367.2007.10599436

Wulf, G., Höß, M., and Prinz, W. (1998). Instructions for motor learning: Differential effects of internal versus external focus of attention. *J. Motor Behav.* 30, 169–179. doi: 10.1080/00222899809601334

You, Y., van der Kamp, J., and Savelsbergh, G. (2024). The relationship between inclination for conscious movement monitoring and control and stopping a golf stroke. *J. Motor Behav.* 12, 1–13. doi: 10.1080/00222895.2024.2375569

Ziv, G., and Lidor, R. (2021). Attentional focus instructions do not affect choice reaction time. *Front. Psychol.* 12:675641. doi: 10.3389/fpsyg.2021.675641

Appendix

Appendix The abbreviations of dependent variables.

Abbreviations	Meanings
CG	Control group
CRTT	Choice reaction time task
CRTT_Correct_Rate	The ratio of correct responses to all responses in the CRTT
CRTT_Go_RT	The mean reaction time on all go trials in the CRTT
EDG	Ego-depletion group
GNG task	Go/no-go task
Go_Correct_RT	The mean reaction time for correct go responses in the GNG task
Go RTV	The variability in reaction time on go trials in the GNG task
High ED group	High ego-depletion group
Low ED group	Low ego-depletion group
MSRS	Movement-Specific Reinvestment Scale
No-Go_Commission_Rate	The ratio of commission errors to all responses on no-go trials in the GNG task
SSD	Stop-signal delay
SSRT	Stop-signal reaction time
SST	Stop-signal task
SST_Go_Correct_Rate	The ratio of correct responses to all responses on go trials in the SST
SST_Go_RT	The mean reaction time on all go trials in the SST
SST_SSD	Mean stop-signal delay
SST_Uncancelled_RT	The mean reaction time on stop trials where participants failed to stop or cancel the response in the SST
SST_Uncancelled_Rate	The ratio of uncancelled responses to all responses on stop trials in the SST
Go_Correct_Rate	The ratio of correct responses to all responses on go trials in the GNG task

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Comparative effects of open-skill and closed-skill sports on executive function in university students: a 16-week quasi-experimental study

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Introduction: Previous reviews have often concluded that open-skill sports are more effective at enhancing executive function (EF) than closed-skill sports. However, this conclusion may not hold for closed-skill sports with high cognitive demands, such as golf. This study aimed to compare the effects of football (open-skill) and golf (closed-skill) training on enhancing EF in university students.

Method: Using a quasi-experimental, pre-post test design, 63 male participants were assigned to three groups: football ($n = 21$), golf ($n = 21$), and a sedentary control group ($n = 21$). Over 16 weeks of training, the intervention groups engaged in four 90-min training sessions per week, while the control group attended one 80-min physical education class per week. Assessments were conducted before and after the intervention. EFs, including inhibition control and working memory, were assessed using the Flanker task and Corsi-block tapping task, respectively. Cardiovascular fitness (CRF) was measured by the multi-stage fitness test.

Results: The golf group showed significant improvements in inhibition control from pre- to post-intervention ($p = 0.02$, $d = 0.26$), while the football and control groups did not exhibit significant changes. Post-intervention comparisons indicated no significant differences in EF performance between the golf and football groups; however, both outperformed the control group (golf, $p = 0.002$, $d = 0.99$; football, $p = 0.01$, $d = 0.67$). No significant improvement was observed in working memory for any group. Additionally, changes in CRF were not significantly correlated with EF performance.

Conclusion: This study provides preliminary evidence that golf, a closed-skill sport with high cognitive demands, can effectively improve inhibitory control after 16 weeks of training. This improvement is comparable to that observed in football, an open-skill sport. The findings also suggest that the cognitive demands of the sports, rather than improvements in physical fitness, may be primarily responsible for the enhancements in EF.

KEYWORDS

soccer, cognition, cognitive function, intervention, golf

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1 Introduction

Executive function (EF) encompasses critical cognitive processes such as information updating, planning, attention, working memory, and problem-solving, all of which are vital for goal-directed behavior and adapting to environmental changes (Diamond, 2013). The COVID-19 pandemic has exacerbated cognitive impairments, including cognitive decline and 'brain fog', underscoring the urgent need for effective strategies to enhance EF (Altuna et al., 2021). Exercise has emerged as a promising intervention to improve EF (De Sousa et al., 2021; Teo and Goodwill, 2022), as evidenced by review studies indicating that various exercise regimens can significantly enhance inhibitory control and working memory in youth, although effect sizes are typically low to moderate (see review, Liu et al., 2020).

While the general benefits of exercise on EF are recognized, the nuanced relationships and underlying mechanisms, especially regarding different types of exercise and EF, remain not well understood (Logan et al., 2023). Studies suggest that the type of cognitive load inherent in different sports may play a critical role in determining their impact on EF (Fuster et al., 2021; Yongtawee et al., 2022). For instance, open-skill sports, such as football, which require constant adaptation to unpredictable environments, may enhance specific aspects of EF differently compared to closed-skill sports like swimming, which involve more predictable and self-paced environments with minimal external variability (Zhu et al., 2020; Russo et al., 2022). Athletes in open-skill sports exhibit more variability in their motor responses, as they must adapt to the specific environmental conditions of each situation. In contrast, closed-skill athletes typically follow set patterns in their motor responses, resulting in greater consistency (Zhu et al., 2020; Russo et al., 2022). This distinction contributes to differences in EF performance between closed-skill athletes and open-skill athletes. Specifically, athletes in open-skill sports have shown superior sustained attention (Ballester et al., 2018), inhibitory control (Wang et al., 2013, 2017), and cognitive flexibility (Yu et al., 2017) compared to athletes in closed-skill sports and non-athletes (Yongtawee et al., 2021). A randomized control trial by Tsai et al. (2017) further supports this distinction, demonstrating that after 6 months of intervention, novel elderly male participants in open-skill exercises (i.e., table tennis) improved reaction times in task-switching tasks, while closed-skill exercises (i.e., bike riding and brisk walking/jogging) enhanced accuracy in memory tasks.

Neuroimaging studies provide further insight into the neurocognitive effects of different sports. Studies using EEG or fMRI have observed that open-skill sports are associated with increased neural efficiency and enhanced connectivity in brain regions related to EF during cognitive tasks (Takahashi and Grove, 2023), and are generally thought to provide greater benefits to EF than closed-skill sports (Wang et al., 2017; Gu et al., 2019; Zhu et al., 2020; Heilmann et al., 2022). However, existing comparisons between open- and closed-skill sports have not sufficiently clarified whether closed-skill exercises with high cognitive demands could lead to similar improvements in EF as open-skill exercises. Most previous studies have focused on closed-skill exercises like running or swimming, which involve minimal cognitive load (see reviews, Gu et al., 2019; Zhu et al., 2020; Heilmann et al., 2022). A closed-skill sport with high cognitive demands, such as golf, might yield different results.

Golf, a closed-skill sport, integrates physical, sensory, cognitive, and social components (Murray et al., 2017; Shimada et al., 2018). Mastering the golf swing requires high levels of hand-eye coordination, static postural control, and sensorimotor control. During a game, strategic planning, information management, and adapting to changing environmental conditions highlight the cognitive demands of golf (Jäncke et al., 2009; Shimada et al., 2018). Studies have examined golf's impact on various aspects of EF, such as attention, inhibition control, working memory, and cognitive feasibility (Gallicchio et al., 2017; Shimada et al., 2018; Roberts et al., 2021; Wang et al., 2020). Currently, most studies focus on its role in enhancing EF and delaying cognitive decline in the elderly. For example, Shimada et al. (2018) found that a 24-week golf training program significantly improved both immediate and delayed logical memory in older adults. Similarly, Stroehlein et al. (2021) reported that elderly individuals with subjective memory complaints who completed a 22-week golf training program performed better in inhibition tasks than a waiting list control group. Bezzola et al. (2011) observed that 40 h of golf practice, conducted as a leisure activity with individualized training, increased grey matter in task-relevant cortical networks involving sensorimotor regions in older adults. Limited studies on younger populations, such as that by Kim et al. (2015), revealed that professional golfers exhibited greater functional connectivity between the cerebellum and frontal lobes compared to non-golfers, indicating enhanced brain functions related to motor control and inhibition. These promising findings warrant further exploration into whether golf can improve EF as effectively as open-skill sports in younger populations.

Football, an open-skill sport, requires continuous adaptation to changing environments, influencing cognitive processes differently than closed-skill sports. Studies indicate that EF significantly influences football performance, correlating with better outcomes in goals and assists, and cognitive abilities can predict performance levels (Vestberg et al., 2017; Sakamoto et al., 2018). Football-related training programs have demonstrated both acute and chronic positive effects on EF. For instance, Won et al. (2017) found that a single session of indoor football among college-aged players significantly impacted brain networks responsible for attention allocation and classification speed during inhibitory control tasks. Dong et al. (2024) reported that 70 sessions of 30-min football juggling over 82 days enhanced young adults' EF performance, particularly in inhibition and shifting, by increasing functional connectivity within the frontal, temporal, and cerebellar regions. Additionally, Xiao et al. (2024) found that a specific football training program improved working memory in adolescents with intellectual disabilities by enhancing activation in the right frontopolar area of the brain.

The mechanisms through which exercise influences EF performance are multifaceted and complex. Cardiovascular fitness (CRF), in particular, has been strongly correlated with EF improvements across numerous studies (e.g., Mekari et al., 2019; Aghjayan et al., 2021; Logan et al., 2023). Football, which combines both aerobic and anaerobic exercise, may be more effective at enhancing CRF compared to golf, suggesting that football could offer greater benefits to EF through improved CRF. However, cognitive training embedded within physical exercise regimens has also been exceptionally effective in enhancing EF (Biazus-Sehn et al., 2020; Gavelin et al., 2021). Although golf typically involves lower exercise intensity, it includes periods of varying intensity and significant cognitive demands (Murray et al., 2017; Shimada et al., 2018), which may render it equally effective as football in improving EF. Given that the relationship between CRF and EF becomes more pronounced after early adulthood (Scisco et al., 2008), university students, who are at a critical stage of EF development, are an ideal group to study the effects of different types of exercise on EF. Improvements in EF during this period can have a significant impact on academic performance, decision-making and overall cognitive health (Diamond, 2013).

To better understand how different forms of exercise impact EF performance, this study aims to compare the effects of football and golf on EF in male university students. Based on the previous literature, we hypothesized that: (1) both football and golf would be effective in enhancing EF compared to a non-exercise group; and (2) the effectiveness of football and golf in enhancing EF would be equivalent.

2 Method

2.1 Participants

Sixty-three male university students were recruited using a convenience sampling strategy. Participants were recruited from the first author's university through advertisements posted on campus. Interested students called the office number listed on the poster and left personal information such as name, contact information, age, and major. Those who met the inclusion criteria were invited to participate, with enrollment continuing until the quota was reached.

Participants were assigned to one of three groups: golf ($n=21$), football ($n=21$), and a sedentary control group ($n=21$). The two intervention groups comprised physical education students with comparable physical fitness scores. After providing consent, participants voluntarily joined either the golf or football group to receive specific training. The control group consisted of students from normal academic classes who exhibited sedentary behavior. Participants' demographic information is listed in Table 1.

Eligibility criteria included no history of injury within 1 month prior to the study, no medication use, no special education needs, and being predominantly right-handed. Additionally, participants were required not to have contracted COVID-19 within the past 3 months. Students completed the International Physical Activity Questionnaire (IPAQ), and only those who reported sitting for at least 540 min per weekday were included in the control group (Bauman et al., 2011; Liang et al., 2024; Scholes et al., 2016).

This study was approved by Guilin Tourism university's research board [Ref. 桂旅科研(2023)-68] and adhered to the principles outlined in the Declaration of Helsinki. All participants were informed of the experimental procedures and potential risks and voluntarily signed consent forms. No participants dropped out of the study, and no financial incentives were provided.

An *a priori* power analysis was performed using G*Power (version 3.1.9; Faul et al., 2007) to determine the minimum sample size needed to achieve a power level of 0.8. This analysis was based on data from a previous study that involved 20 participants per group (Ballester et al., 2018), comparing performance on the psychomotor vigilance task among adolescent football athletes, track and field athletes, and age-matched non-athlete controls. Accounting for a 5% dropout rate, a total of 63 individuals were required.

TABLE 1 Demographic information.

Groups	Golf	Football	Control
Age (years)	20.95 (1.02)	20.81 (0.98)	20.62 (0.87)
Heart rate (/min)	65.33 (6.191)	63.62 (5.4)	73.43 (6.49)
BMI	23.1 (1.73)	22.56 (1.55)	24.04 (2.63)
IPAQ (METS)	4650.57 (837.3)	3932.71 (903.79)	1399.81 (506.88)

Data are presented as mean (SD). BMI indicates the body mass index. IPAQ indicates the general physical activity level out of training over the last 7 days during the intervention.

2.2 Design and procedure

A single-blinded, quasi-experimental pre-posttest design was employed. Two trained assessors, blinded to the research aims, conducted all assessments and did not participate in the intervention. Baseline (pre-test) assessments were conducted at the beginning of the academic year, starting on September 4 and lasting for 2 weeks. These assessments included measurements of demographic information, CRF, and EFs such as inhibition control and working memory. Participants then underwent a 16-week intervention starting on September 19, involving golf, football, or control (i.e., physical education classes) based on their group assignment. Post-intervention assessments of CRF and EFs were conducted on January 8 of the following year. To account for other physical activities outside of class that might affect EF performance at post-test, participants were asked to report their daily physical activity levels.

On testing days, participants were prohibited from consuming beverages containing caffeine or alcohol and from engaging in any strenuous physical activities for the 24 h prior to visiting the lab. They were instructed to maintain a consistent diet in the days and hours before the testing day to minimize variations from baseline tests. This ensured that test results were not affected by participants' nutritional status.

The pre-test procedure began with the collection of demographic information. Participants completed demographic information forms, and each participant's body weight and BMI were measured using a composition analyzer (In Body 570, Cerritos, CA, USA). Subsequently, they performed the EF tasks in a quiet classroom with dim lighting. Participants were positioned 30–80 cm from the screen, adjusted for their vision and height. To minimize learning effects, participants practiced the test battery twice before formal testing. The tasks were administered in a consistent order, starting with the Flanker task to measure inhibition control (Eriksen and Eriksen, 1974) followed by the Corsi-block backward task to measure working memory (Corsi, 1972; Kessels et al., 2008), with a 2-min rest between tasks. Performance was automatically recorded by the computer.

CRF assessments were performed last. Participants completed a 10-min warm-up consisting of a 400-meter jog and stretching exercises, followed by the 20-m shuttle run version of the multi-stage fitness test on an outdoor playground to assess maximal oxygen consumption (VO2 max) for CRF evaluation. Participants continued the shuttle runs in sync with audio cues until they reached voluntary exhaustion or could no longer maintain the required pace. Assessors recorded the levels and number of shuttles for further analysis.

The post-test followed the same procedure as the pre-test, with EF tasks conducted first, followed by the CRF assessments. Daily physical activity outside of training classes was recorded (i.e., IPAQ) at last. Testing sessions were scheduled in the morning or afternoon, depending on participants' availability.

2.3 Intervention

The intervention period lasted 16 weeks, during which participants in the intervention groups (golf and football) engaged in specific training sessions led by qualified coaches, while the control group continued their regular physical education classes. Each intervention group participated in four 90-min training sessions per week, while the control group attended one 80-min physical education class per week. The content of the training sessions varied according to the assigned group:

Participants in the golf group received the following training: (1) Driving range practice: focused on developing swing techniques and improving distance control. (2) Course play: practical application of skills in a real-game setting to enhance strategic thinking and course management. (3) Putting practice: aimed at refining precision and accuracy in short-distance shots. (4) Strength training: included exercises to improve overall muscular strength and endurance, which are essential for maintaining form and reducing injury risk during swings.

Participants in the football group received the following training: (1) Ball control exercises: drills designed to enhance dribbling, passing, and receiving skills. (2) Skills training: focused on specific football techniques such as kicking, dribbling, and shooting. (3) Skill combination drills: combine various skills in a single exercise to simulate real-game scenarios and improve overall gameplay. (4) Opposition drills: practiced against defenders to develop tactical awareness and decision-making under pressure. (5) Standard matches: regular gameplay to apply learned skills in a competitive environment. (6) Physical conditioning: included aerobic and anaerobic exercises to improve cardiovascular fitness, speed, and agility.

Participants in the control group engaged in general physical education activities that were less structured and of lower intensity compared to the intervention groups. These activities included: (1) General fitness exercises: such as jogging, stretching, and light aerobic activities with minor strength training. (2) Sports of individual choice: activities chosen by the participants, typically performed at low to moderate intensity levels.

During the intervention, coaches strictly adhered to the training plans to prevent injuries and ensure participant well-being. Participants were instructed to immediately report to the coach if they felt the training intensity was too high or if they experienced any discomfort or potential injury, allowing them to rest as needed. The training program was only interrupted by adverse weather conditions and public holidays. During bad weather, indoor classes focusing on the theoretical knowledge of the respective sports were conducted. Adherence rates were recorded by the coaches throughout the intervention period, resulting in 98.21% adherence in the football group, 98.59% in the golf group, and 94.64% in the control group.

2.4 Measurement

2.4.1 Executive function

The Psytoolkit battery was used to assess EF performance (Stoet, 2010, 2017). In Flanker task (Eriksen and Eriksen, 1974), participants sat in front of a computer screen and saw five letters appearing above a fixation point (a white cross). At the start of the test, they had to respond only to the central letter, by pressing the A button on the keyboard (if the central letter was either X or C), or by pressing the L button (if the central letter was either V or B). If the flanking letters' response does not match the response required by the central letter, we refer to it as an "incongruent" condition. Participants were given 50 trials and were asked to respond as quickly and accurately as possible. Participants underwent two blocks of 25 trials each. The 50 trials presented in this task were distributed equally among the two experimental conditions and were presented in a random order. Participants had 2 s to provide their response to the correct letter. Performance was recorded by corrected reaction time (ms) in two different conditions, as it address the speed–accuracy interactions for EF performance (Draheim et al., 2019).

In Corsi-block backward task (Corsi, 1972; Kessels et al., 2008), participants were instructed to use their computer mouse to click through a series of up to nine previously highlighted blocks in reverse order. This modification of the task not only required participants to maintain the information given but to also manipulate its order, making this version more cognitively taxing than the traditional Corsi-block task which needs to click with the same order (Kessels et al., 2008). The blue squares briefly change color to yellow in a sequence, and once the sequence is complete, an auditory ("Go") alert notified the participant to click the squares in the reverse order they saw them change color. The blocks started with the 2 blocks, should the participant tap the given sequence correctly, they moved on to a more complicated one, with one block added. The test was discontinued when a participant incorrectly indicated the pattern twice. The participant's scores were the highest level reached before the discontinue rule was met. For example, if a participant correctly indicated the pattern at two, three, four, and five squares, and then indicated the incorrect pattern twice at six squares, then their score on the Corsi task was five. The number of blocks was recorded for performance analysis.

2.4.2 Cardiorespiratory fitness

The 20-meter shuttle run version of the multi-stage fitness test were used to assess maximal oxygen consumption ($VO_{2\,max}$) for CRF evaluation (Léger and Lambert, 1982). The starting speed was 8.5 km/h, which increased by 0.5 km/h every minute. $VO_{2\,max}$ was then estimated using an online calculator based on the equation developed by Léger et al. (1988), which was calculated by the participants' performance data (i.e., levels and number of shuttles) from the multi-stage fitness test.

2.4.3 International physical activity questionnaire

The short version of the International Physical Activity Questionnaire (IPAQ) is frequently utilized in academic research to quantify physical activity levels among populations (Lee et al., 2011; Liang et al., 2022). This survey includes 7 questions that cover various intensities of physical activity—vigorous, moderate, and walking—as well as sitting time over the last 7 days. Results from the IPAQ expressed in terms of metabolic equivalent tasks (METs) minutes per week, providing a standardized metric for comparing physical activity levels across different studies and demographic groups. Notably, for participants in the golf group, on-course training (i.e., playing 9 or 18 holes) is classified as moderate activity, while practice on hitting mats and the driving range is classified as walking (Eigendorf et al., 2020; Scalise et al., 2024).

2.5 Statistical analysis

Preliminary analysis was conducted. Outliers were identified using boxplots and *z*-scores, with values exceeding ±3 standard deviations (SD) considered potential outliers. However, even if a value exceeded 3 SD, it was retained in the analysis as long as it remained within the normal measurement range, to better reflect real-life data variability. Minor instances of missing data were addressed using mean substitution.

A repeated-measures analysis of variance (ANOVA) with three groups (golf, football, and control) and two time points (pretest and posttest) was conducted to examine the between- and within-condition effects on EF and CRF. EF performance was analyzed separately for the congruent and incongruent conditions of the Flanker task, as well as the Corsi-block backward task. If a significant effect was observed, *post hoc* tests with Bonferroni correction were performed. The Pearson correlation test was used to examine the association between CRF and EF performance at post-test. Effect size is presented as partial eta squared (η^2) for ANOVA and Cohen's d for *post hoc* comparison. The significance level was set to 0.05. Effect sizes of η^2 and d of 0.01, 0.06, 0.14; and 0.2, 0.5, 0.8 were considered as the small, medium and large effects. Statistical analyses were performed using SPSS (version 29, IBM SPSS, Armonk, NY, USA).

3 Results

3.1 Flanker task

3.1.1 Congruent

The interaction effect between groups and time was not significant, $F(2, 40) = 2.5$, $p = 0.10$, $\eta^2 = 0.11$. Furthermore, there were no significant main effects for either group $F(2, 40) = 0.92$, $p = 0.41$, $\eta^2 = 0.04$, or time, $F(1, 20) = 1.32$, $p = 0.26$, $\eta^2 = 0.06$. (see Figure 1 and Table 2).

3.1.2 Incongruent

The interaction effect between groups and time was significant $F(2, 40) = 6.97$, $p = 0.003$, $\eta^2 = 0.26$. However, neither the main effects of groups, $F(2, 40) = 2.02$, $p = 0.15$, $\eta^2 = 0.09$, nor time, $F(1, 20) = 0.01$, $p = 0.94$, $\eta^2 < 0.001$ were significant. *Post hoc* analysis showed a significant reduction in reaction time for the golf group from pre- to post-test ($p = 0.018$, $d = 0.26$). However, the changes in the football group ($p = 0.09$) and the control group ($p = 0.04$) were not significant after Bonferroni adjustment. At post-test, both the golf group ($p = 0.002$, $d = 0.99$) and the football group ($p = 0.01$, $d = 0.67$) performed better than the control group. However, no significant difference was found between the golf and football groups post-intervention ($p = 0.50$) (see Figure 1 and Table 2).

3.2 Corsi-block backward task

The interaction effect between groups and time was not significant, $F(2, 40) = 0.34$, $p = 0.72$, $\eta^2 = 0.02$. Furthermore, there were no significant main effects for either group, $F(2, 40) = 0.25$, $p = 0.78$, $\eta^2 = 0.01$ or time, $F(1, 20) = 2.80$, $p = 0.11$, $\eta^2 = 0.12$. (See Figure 2 and Table 2).

3.3 Cardiovascular fitness

The interaction between groups and time was not significant, $F(2, 40) = 2.86$, $p = 0.07$, $\eta^2 = 0.13$. The main effect of time was not significantly different, $F(1, 20) = 0.22$, $p = 0.65$, $\eta^2 = 0.01$. However, there was a significant main effect of groups, $F(2, 40) = 54.75$, $p < 0.001$, $\eta^2 = 0.73$. Pairwise comparisons with Bonferroni correction revealed that, regardless time effect, both the golf and football groups had

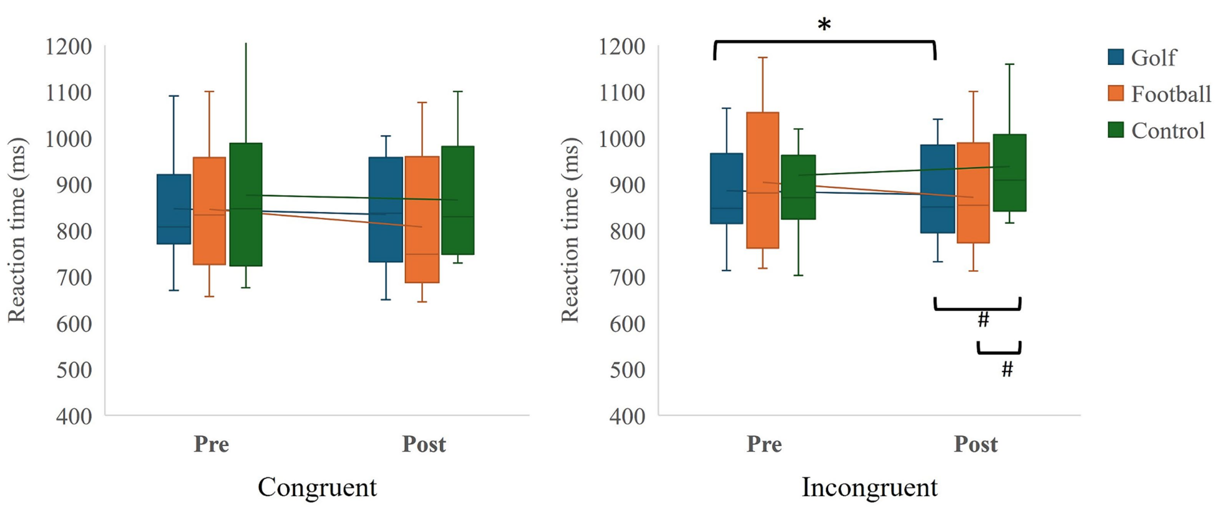

FIGURE 1
Flanker task. * Pre-post comparison with Bonferroni correction $p < 0.05$; # comparisons at post-test with Bonferroni correction $p < 0.05$.

TABLE 2 Performance of executive tasks.

Variables	Golf	Football	Control	Golf	Football	Control
		Pre			Post	
FT						
Congruent	846.38 (113.23)	845.33 (139.12)	875.48 (171.84)	814.71 (117.53)	834.43 (140.40)	893.33 (126.84)
Incongruent	885.67 (106.00)	903.90 (148.49)	918.76 (160.74)	859.14 (96.12) *,#	883.05 (127.24) #	964.29 (115.98)
CBBT						
	6.43 (0.93)	6.48 (0.68)	6.43 (0.87)	6.52 (0.87)	6.81 (1.03)	6.67 (1.15)

Data are presented as mean (SD). FT indicates the Flanker task (reaction time); CBBT indicates the Corsi-block backward task (corrected numbers). *$p < 0.05$ compared with pre-test after Bonferroni correction. #$p < 0.05$ compared with control group at post-test after Bonferroni correction.

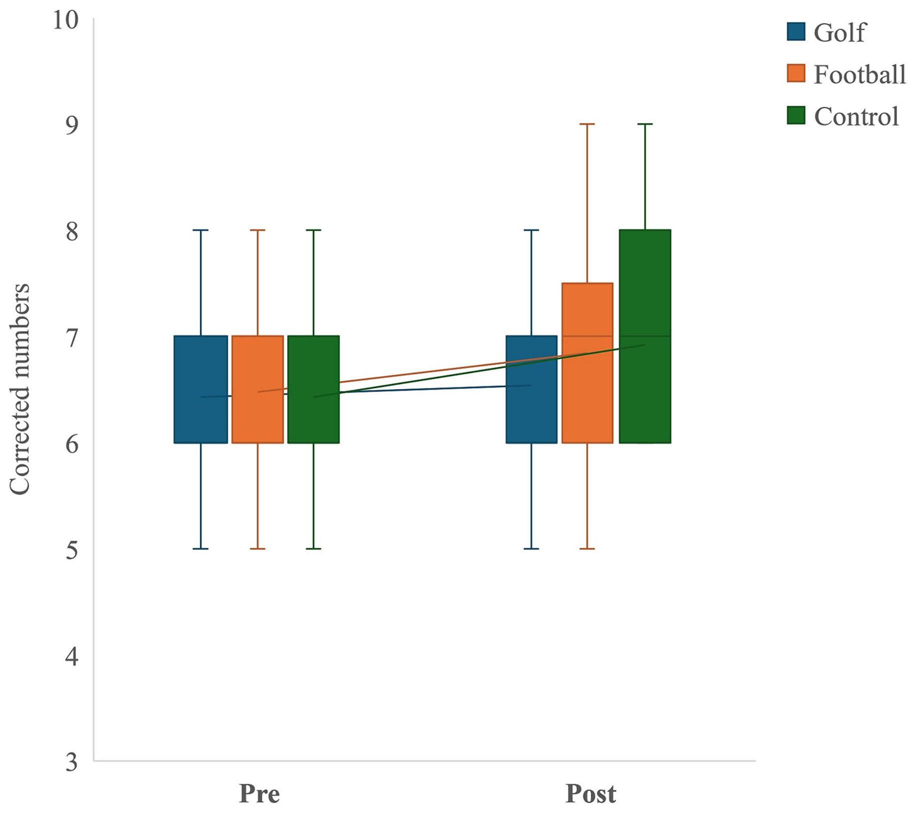

FIGURE 2
Corsi-block backward task.

significantly higher CRF scores compared to the control group (all $p < 0.001$) (Figure 3).

Correlation analyses indicated that there were no significant associations between VO_{2max} and EF performance on the Flanker task congruent condition ($r = -0.16$, $p = 0.20$) or incongruent condition ($r = -0.18$, $p = 0.16$). Additionally, no significant correlation was found between VO_{2max} and CBBT task ($r = -0.30$, $p = 0.80$).

4 Discussion

This study investigated the effects of football (open-skills) and golf (closed-skills) on executive function improvement in male university students. After 16 weeks of training, the golf group demonstrated significant improvements in inhibition control compared to their pre-training levels, while no significant improvement was observed in the football or control groups. However, the golf group did not show superior performance to the football group at post-training, although both intervention groups outperformed the control group. Notably, cardiovascular fitness did not change significantly and was not correlated with changes in EF, suggesting that the observed improvements in EF may be more closely related to the cognitive demands of the interventions rather than changes in physical fitness. These findings could inform strategies for integrating sports into educational and health interventions, ultimately contributing to improved cognitive outcomes across various populations.

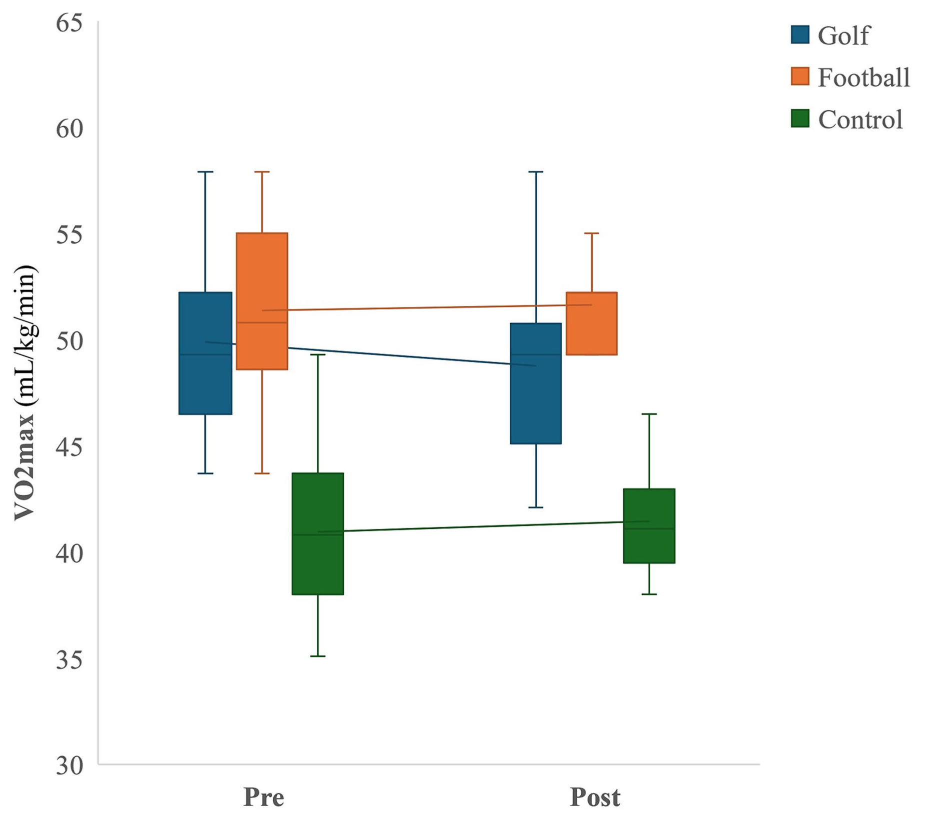

FIGURE 3
Cardiovascular fitness.

The results support our hypothesis that golf, as a close-skill exercise with high cognitive demand, was effective in enhancing inhibition control after training. This finding aligns with Wang et al. (2020), who found that elite golfers exhibited stronger inhibitory control compared to amateurs, as measured by EEG, showing higher levels of attention to motor programming, visuospatial processing, and reduced cognitive-motor interference before putting. However, the precise mechanisms underlying these improvements remain unclear. One possible explanation is that the intense focus, strategic thinking, and precise motor control required in golf engage neural circuits associated with EF, particularly those governing inhibitory control. Since performing complex, multitasking tasks in stressful environments can enhance connectivity within large neurocognitive networks (Kim et al., 2017), the cognitive demands of golf may provide sufficient stimulation to produce lasting improvements in EF (Gallicchio et al., 2017; Shimada et al., 2018; Roberts et al., 2021; Wang et al., 2020). Additionally, golf training may also increase handgrip strength, which has been linked to enhanced EF in previous studies (Carson, 2018; Zhu et al., 2022). Interestingly, we observed no significant improvement in working memory between the groups, which is consistent with Lineweaver et al. (2019), who observed that frequent exercise is not associated with better working memory capacity than infrequent exercise in non-athlete college students. Similarly, Song et al. (2024) found that while there was no significant difference in working memory task performance between athletes and non-athletes at the behavioral level, although functional near-infrared spectroscopy (fNIRS) revealed differences in prefrontal cortex activation during the task.

Our finding is in contrast to previous reviews that have generally concluded that open-skill sports are more effective at enhancing EF due to their association with increased neural efficiency during cognitive tasks (Gu et al., 2019; Zhu et al., 2020; Heilmann et al., 2022; Takahashi and Grove, 2023). This discrepancy may arise because prior studies on closed-skill exercises primarily focused on activities with minimal cognitive load, such as running or swimming, potentially lacking persuasive evidence (Heilmann et al., 2022). As a result, these comparisons have not fully explored whether closed-skill exercises with high cognitive demands, like golf, can produce similar EF improvements as open-skill exercises. Our study addresses this gap in the literature by directly comparing the effects of open-skill and closed-skill sports on EF in a controlled setting. This is particularly significant as previous research has not adequately examined the role of cognitive load in determining EF outcomes across different types of sports.

Interestingly, unlike previous studies, football did not lead to significant improvements in EF in our study. This finding may be attributed to the fact that the participants had already reached sub-elite levels of physical fitness, necessitating more challenging stimuli to achieve further EF gains. It's possible that the relationship between CRF and EF follows a curvilinear pattern, where increases in CRF beyond a certain threshold have diminishing or negligible effects on EF improvement. However, to our best knowledge, no studies have identified this relationship or established a cutoff value to delineate this threshold. This might also explain the inconsistencies observed in previous studies, where most acknowledge a correlation between CRF and EF (Mekari et al., 2019; Aghjayan et al., 2021; Logan et al., 2023), while some report no significant relationship (Tuvey et al., 2019; Meijer et al., 2021). Based on our findings, for individuals who have already achieved moderate to high levels of CRF, interventions with greater cognitive load may be more effective in stimulating and enhancing EF.

Regarding the observation that both intervention groups performed better than the control group in post-test inhibition control, this finding is consistent with mainstream research that suggests exercise can enhance EF performance in youth (Liu et al., 2020; Li et al., 2022). The athletes generally exhibit better EF compared to sedentary or non-athletic individuals, especially for attention and inhibition control capacity (Jacobson and Matthaeus, 2014; Sharma et al., 2019). This suggests that increasing physical activity may be an effective strategy for improving EF performance in sedentary students. For instance, Wu et al. (2022) found that breaking up prolonged sitting with light-intensity exercise can enhance attention, EFs, and mood. The findings highlight the importance of incorporating regular exercise into the routines of sedentary students (Zhu et al., 2024), in order to improve their EF performance and well-being.

The findings of this study have significant implications for both research and practice. Our results contribute to the growing evidence that integrating cognitive demands into exercise training can enhance EF more effectively than merely increasing exercise intensity. This aligns with studies by Biazus-Sehn et al. (2020) and Gavelin et al. (2021), which demonstrate that combining cognitive challenges with physical activity leads to superior cognition improvements. Additionally, our findings suggest that for individuals with moderate to high levels of physical fitness, engaging directly in cognitively demanding activities appears to be an effective targeted intervention for enhancing EF. This is further supported by Casella et al. (2022), who found that a 10-week cognitive-motor training program integrated into standard football training significantly improved planning abilities and visual search in young football players. Similarly, Kolovelonis and Goudas (2023) found that primary students involved in cognitively challenging games showed greater improvements in EF performance compared to those in football, track and field, and control groups after 1 month of intervention.

This study has several limitations. First, the effect size for the improvement observed in the golf group from pre- to post-test is relatively small, the result should be interpreted with caution. Second, only male college athletes were recruited, which limits the generalizability of our findings to other populations. Third, this study employed convenience sampling, which may have introduced bias into the statistical results (Duan et al., 2022). Future studies are recommended to use random sampling to strengthen the findings. Fourth, our research focused on behavioral outcomes; due to experimental constraints, we did not use neuroimaging techniques (e.g., EEG, fNIRS) or measure the biomarkers (e.g., brain-derived neurotrophic factors and catecholamines) which relatively with EF changes.

5 Conclusion

This study provides preliminary evidence that golf, a closed-skill sport with high cognitive demands, can effectively improve inhibitory control after 16 weeks of training. While this improvement in EF is comparable to the gains observed in football, an open-skill sport, it underscores the cognitive health benefits that closed-skill sports may provide. Further research is needed to explore the underlying neural mechanisms and to determine whether similar improvements can be achieved in broader populations.

Data availability statement

The datasets used and/or analyzed in the current study are available from the corresponding author upon reasonable request.

Ethics statement

The studies involving humans were approved by University Human Research Ethics Committee [Ref. 桂旅科研 (2023)-68]/Guilin Tourism 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

Y-fL: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. TG: Writing – review & editing, Methodology, Conceptualization. L-pL: Writing – original draft, Data curation, Conceptualization. SH: Writing – review & editing, Methodology, Conceptualization.

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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.

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References

Aghjayan, S. L., Lesnovskaya, A., Esteban-Cornejo, I., Peven, J. C., Stillman, C. M., and Erickson, K. I. (2021). Aerobic exercise, cardiorespiratory fitness, and the human hippocampus. *Research Square (Preprint)* 31, 817–844. doi: 10.1002/hipo.23337

Altuna, M., Sánchez-Saudinós, M. B., and Lleó, A. (2021). Cognitive symptoms after COVID-19. *Neurol. Perspect.* 1, S16–S24. doi: 10.1016/j.neurop.2021.10.005

Ballester, R., Huertas, F., Molina, E., and Sanabria, D. (2018). Sport participation and vigilance in children: influence of different sport expertise. *J. Sport Health Sci.* 7, 497–504. doi: 10.1016/j.jshs.2017.05.008

Bauman, A., Ainsworth, B. E., Sallis, J. F., Hagströmer, M., Craig, C. L., Bull, F. C., et al. (2011). The descriptive epidemiology of sitting: a 20-country comparison using the international physical activity questionnaire (IPAQ). *Am. J. Prev. Med.* 41, 228–235. doi: 10.1016/j.amepre.2011.05.003

Bezzola, L., Mérillat, S., Gaser, C., and Jäncke, L. (2011). Training-induced neural plasticity in golf novices. *J. Neurosci.* 31, 12444–12448. doi: 10.1523/JNEUROSCI.1996-11.2011

Biazus-Sehn, L. F., Schuch, F. B., Firth, J., Stigger, F., and De, S. (2020). Effects of physical exercise on cognitive function of older adults with mild cognitive impairment: a systematic review and meta-analysis. *Arch. Gerontol. Geriatr.* 89:104048. doi: 10.1016/j.archger.2020.104048

Carson, R. G. (2018). Get a grip: individual variations in grip strength are a marker of brain health. *Neurobiol. Aging* 71, 189–222. doi: 10.1016/j.neurobiolaging.2018.07.023

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

Corsi, P. M. (1972). Human memory and the medial temporal region of the brain.

De Sousa, R. A. L., Improta-Caria, A. C., Aras-Júnior, R., de Oliveira, E. M., Soci, Ú. P. R., and Cassilhas, R. C. (2021). Physical exercise effects on the brain during COVID-19 pandemic: links between mental and cardiovascular health. *Neurol. Sci.* 42, 1325–1334. doi: 10.1007/s10072-021-05082-9

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

Dong, X., Gui, X., Klich, S., Zhu, L., Chen, D., Sun, Z., et al. (2024). The effects of football juggling learning on executive function and brain functional connectivity. *Front. Hum. Neurosci.* 18:1362418. doi: 10.3389/fnhum.2024.1362418

Draheim, C., Mashburn, C. A., Martin, J. D., and Engle, R. W. (2019). Reaction time in differential and developmental research: a review and commentary on the problems and alternatives. *Psychol. Bull.* 145, 508–535. doi: 10.1037/bul0000192

Duan, Y., Liang, W., Wang, Y., Lippke, S., Lin, Z., Shang, B., et al. (2022). The effectiveness of sequentially delivered web-based interventions on promoting physical activity and fruit-vegetable consumption among Chinese college students: mixed methods study. *J. Med. Internet Res.* 24:e30566. doi: 10.2196/30566

Eigendorf, J., Korallus, C., Riedel, T., Schäring, U., and Tegtbur, U. (2020). Energy consumption in golf: classifying golf by physical activity guideline. *Research Square (Preprint)*. doi: 10.21203/rs.3.rs-99133/v1

Eriksen, B. A., and Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Percept. Psychophys.* 16, 143–149. doi: 10.3758/BF03203267

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

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

Gallicchio, G., Cooke, A., and Ring, C. (2017). Practice makes efficient: cortical alpha oscillations are associated with improved golf putting performance. *Sport Exerc. Perform. Psychol.* 6, 89–102. doi: 10.1037/spy0000077

Gavelin, H. M., Dong, C., Minkov, R., Bahar-Fuchs, A., Ellis, K. A., Lautenschlager, N. T., et al. (2021). Combined physical and cognitive training for older adults with and without cognitive impairment: a systematic review and network meta-analysis of randomized controlled trials. *Ageing Res. Rev.* 66:101232. doi: 10.1016/j.arr.2020.101232

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

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

Jacobson, J. H., and Matthaeus, L. (2014). Athletics and executive functioning: how athletic participation and sport type correlate with cognitive performance. *Psychol. Sport Exerc.* 15, 521–527. doi: 10.1016/J.PSYCHSPORT.2014.05.005

Jäncke, L., Koeneke, S., Hoppe, A., Rominger, C., and Hänggi, J. (2009). The architecture of the Golfer's brain. *PLoS One* 4:e4785. doi: 10.1371/journal.pone.0004785

Kessels, R. P. C., van den Berg, E., Ruis, C., and Brands, A. M. A. (2008). The backward span of the corsi block-tapping task and its association with the wais-iii digit span. *Assessment* 15, 426–434. doi: 10.1177/1073191108315611

Kim, J. H., Han, J., Kim, B.-N., and Han, D. (2015). Brain networks governing the golf swing in professional golfers. *J. Sports Sci.* 33, 1980–1987. doi: 10.1080/02640414.2015.1022570

Kim, N. Y., Wittenberg, E., and Nam, C. S. (2017). Behavioral and neural correlates of executive function: interplay between inhibition and updating processes. *Front. Neurosci.* 11:378. doi: 10.3389/fnins.2017.00378

Kolovelonis, A., and Goudas, M. (2023). Acute enhancement of executive functions through cognitively challenging physical activity games in elementary physical education. *Eur. Phys. Educ. Rev.* 29, 268–285. doi: 10.1177/1356336X221135139

Lee, P. H., Macfarlane, D. J., Lam, T., and Stewart, S. M. (2011). Validity of the international physical activity questionnaire short form (ipaq-sf): a systematic review. *Int. J. Behav. Nutr. Phys. Act.* 8:115. doi: 10.1186/1479-5868-8-115

Léger, L. A., and Lambert, J. (1982). A maximal multistage 20-m shuttle run test to predict VO_2 max. *Europ. J. Appl. Physiol.* 49, 1–12. doi: 10.1007/BF00428958

Léger, L. A., Mercier, D., Gadoury, C., and Lambert, J. (1988). The multistage 20 metre shuttle run test for aerobic fitness. *J. Sports Sci.* 6, 93–101. doi: 10.1080/02640418808729800

Li, S., Guo, J., Zheng, K., Shi, M., and Huang, T. (2022). Is sedentary behavior associated with executive function in children and adolescents? A systematic review. *Front. Public Health* 10:832845. doi: 10.3389/fpubh.2022.832845

Liang, W., Duan, Y., Wang, Y., Lippke, S., Shang, B., Lin, Z., et al. (2022). Psychosocial mediators of web-based interventions for promoting a healthy lifestyle among Chinese college students: secondary analysis of a randomized controlled trial. *J. Med. Internet Res.* 24:e37563. doi: 10.2196/37563

Liang, W., Wang, Y., Huang, Q., Shang, B., Su, N., Zhou, L., et al. (2024). Adherence to 24-hour movement guidelines among Chinese older adults: prevalence, correlates, and associations with physical and mental health outcomes. *JMIR Public Health Surveill.* 10:e46072. doi: 10.2196/46072

Lineweaver, T. T., Kercood, S., Morgan, E. B., Rampone, S. L., Frank, C. C., McLuckie, S. A., et al. (2019). Working memory in collegiate athletes and non-athletes: a comparison of team-sports athletes, solo-sports athletes, frequent exercisers and infrequent exercisers. *OBM Integrat. Complement. Med.* 5, 1–14. doi: 10.21926/obm.icm.2001002

Liu, S., Yu, Q., Li, Z., Cunha, P. M., Zhang, Y., Kong, Z., et al. (2020). Effects of acute and chronic exercises on executive function in children and adolescents: a systemic review and meta-analysis. *Front. Psychol.* 11:554915. doi: 10.3389/fpsyg.2020.554915

Logan, N. E., Henry, D. A., Hillman, C. H., and Kramer, A. F. (2023). Trained athletes and cognitive function: a systematic review and meta-analysis. *Int. J. Sport Exerc. Psychol.* 21, 725–749. doi: 10.1080/1612197X.2022.2084764

Meijer, A., Königs, M., de Bruijn, A. G. M., Visscher, C., Bosker, R. J., Hartman, E., et al. (2021). Cardiovascular fitness and executive functioning in primary school-aged children. *Dev. Sci.* 24:e13019. doi: 10.1111/desc.13019

Mekari, S., Dupuy, O., Martins, R., Evans, K., Kimmerly, D. S., Fraser, S., et al. (2019). The effects of cardiorespiratory fitness on executive function and prefrontal oxygenation in older adults. *GeroScience* 41, 681–690. doi: 10.1007/s11357-019-00128-5

Murray, A. D., Daines, L., Archibald, D., Hawkes, R. A., Schiphorst, C., Kelly, P., et al. (2017). The relationships between golf and health: a scoping review. *Br. J. Sports Med.* 51, 12–19. doi: 10.1136/bjsports-2016-096625

Roberts, L., Jackson, M., and Grundy, I. (2021). The effects of cognitive interference during the preparation and execution of the golf swing. *Int. J. Sport Exerc. Psychol.* 19, 413–428. doi: 10.1080/1612197X.2019.1674901

Russo, G., Bigliassi, M., Ceciliani, A., and Tessari, A. (2022). Exploring the interplay between sport modality and cognitive function in open- and closed-skill athletes. *Psychol. Sport Exerc.* 61:102186. doi: 10.1016/j.psychsport.2022.102186

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

Scalise, F., Cavanna, F., Godio, C., and Beretta, E. P. (2024). Exercise intensity and activity energy expenditure of professional golf players in official competitive setting. *Sports Health* 16, 481–486. doi: 10.1177/19417381231175149

Scholes, S., Bridges, S., Ng Fat, L., and Mindell, J. S. (2016). Comparison of the physical activity and sedentary behaviour assessment questionnaire and the short-form international physical activity questionnaire: an analysis of health survey for England data. *PLoS One* 11:e0151647. doi: 10.1371/journal.pone.0151647

Scisco, J. L., Leynes, P. A., and Kang, J. (2008). Cardiovascular fitness and executive control during task-switching: an ERP study. *Int. J. Psychophysiol.* 69, 52–60. doi: 10.1016/j.ijpsycho.2008.02.009

Sharma, V. K., Subramanian, S. K., and Rajendran, R. (2019). Comparison of cognitive auditory event related potentials and executive functions in adolescent athletes and non-athletes - a cross sectional study. *Int. J. Physiol. Pathophysiol. Pharmacol.* 11, 274–282

Shimada, H., Lee, S., Akishita, M., Kozaki, K., Iijima, K., Nagai, K., et al. (2018). Effects of golf training on cognition in older adults: a randomised controlled trial. *J. Epidemiol. Community Health* 72, 944–950. doi: 10.1136/jech-2017-210052

Song, Y.-T., Xiang, M.-Q., and Zhong, P. (2024). Differences in brain activation during working memory tasks between badminton athletes and non-athletes: an fNIRS study. *Brain Cogn.* 175:106133. doi: 10.1016/j.bandc.2024.106133

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). PsyToolkit. *Teach. Psychol.* 44, 24–31. doi: 10.1177/0098628316677643

Stroehlein, J. K., Vieluf, S., Zimmer, P., Schenk, A., Oberste, M., Goelz, C., et al. (2021). Learning to play golf for elderly people with subjective memory complaints: feasibility of a single-blinded randomized pilot trial. *BMC Neurol.* 21:200. doi: 10.1186/s12883-021-02186-9

Takahashi, S., and Grove, P. M. (2023). Impact of acute open-skill exercise on inhibitory control and brain activation: a functional near-infrared spectroscopy study. *PLoS One* 18:e0276148. doi: 10.1371/journal.pone.0276148

Teo, W.-P., and Goodwill, A. M. (2022). Can exercise attenuate the negative effects of long COVID syndrome on brain health? *Front. Immunol.* 13:986950. doi: 10.3389/fimmu.2022.986950

Tsai, C.-L., Pan, C.-Y., Chen, F.-C., and Tseng, Y.-T. (2017). Open- and closed-skill exercise interventions produce different neurocognitive effects on executive functions in the elderly: a 6-month randomized, controlled trial. *Front. Aging Neurosci.* 9:294. doi: 10.3389/fnagi.2017.00294

Tuvey, S. D. J., Steele, J., Horton, E., Mayo, X., Liguori, G., Mann, S., et al. (2019). Do changes in cardiorespiratory fitness resulting from physical activity interventions impact academic performance and executive function in children and adolescents? A systematic review, meta-analysis, and meta-regression. Sports Med. Available at: https://osf.io/preprints/sportrxiv/4j2sa/ (Accessed June 29, 2024)

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

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

Wang, K.-P., Cheng, M.-Y., Chen, T.-T., Huang, C.-J., Schack, T., and Hung, T.-M. (2020). Elite golfers are characterized by psychomotor refinement in cognitive-motor processes. *Psychol. Sport Exerc.* 50:101739. doi: 10.1016/j.psychsport.2020.101739

Wang, C.-H., Yang, C.-T., Moreau, D., and Muggleton, N. G. (2017). Motor expertise modulates neural oscillations and temporal dynamics of cognitive control. *NeuroImage* 158, 260–270. doi: 10.1016/j.neuroimage.2017.07.009

Won, J., Wu, S., Ji, H., Smith, J. C., and Park, J. (2017). Executive function and the p300 after treadmill exercise and futsal in college soccer players. *Sports* 5:73. doi: 10.3390/sports5040073

Wu, Y., van Gerven, P., de Groot, R. H. M., Eijnde, B. O., Winkens, B., Savelberg, H. H. C. M., et al. (2022). Effects of breaking up sitting with light-intensity physical activity on cognition and mood in university students. *Scand. J. Med. Sci. Sports* 33, 257–266. doi: 10.1111/sms.14277

Xiao, R., Xu, P., Liang, X.-L., Zou, Z., Zhong, J.-G., Xiang, M.-Q., et al. (2024). Effects of the special olympics unified sports soccer training program on executive function in adolescents with intellectual disabilities. *J. Exercise Sci. Fitness* 22, 103–110. doi: 10.1016/j.jesf.2023.12.006

Yongtawee, A., Park, J., Kim, Y., and Woo, M. (2022). Athletes have different dominant cognitive functions depending on type of sport. *Int. J. Sport Exerc. Psychol.* 20, 1–15. doi: 10.1080/1612197X.2021.1956570

Yongtawee, A., Park, J.-H., and Woo, M.-J. (2021). Does sports intelligence, the ability to read the game, exist? A systematic review of the relationship between sports performance and cognitive functions. *J. Korea Converg. Soc.* 12, 325–339. doi: 10.15207/JKCS.2021.12.3.325

Yu, Q., Chan, C. C. H., Chau, B., and Fu, A. S. N. (2017). Motor skill experience modulates executive control for task switching. *Acta Psychol.* 180, 88–97. doi: 10.1016/j.actpsy.2017.08.013

Zhu, Y., Chan, D. K. C., Pan, Q., Rhodes, R. E., and Tao, S. (2024). National trends and ecological factors of physical activity engagement among U.S youth before and during the COVID-19 pandemic: a cohort study from 2019 to 2021. *BMC Public Health* 24:1923. doi: 10.1186/s12889-024-19486-7

Zhu, H., Chen, A., Guo, W., Zhu, F., and Wang, B. (2020). Which type of exercise is 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

Zhu, Y., He, S., Herold, F., Sun, F., Li, C., Tao, S., et al. (2022). Effect of isometric handgrip exercise on cognitive function: current evidence, methodology, and safety considerations. *Front. Physiol.* 13:1012836. doi: 10.3389/fphys.2022.1012836

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Axial rotation affects the cognitive characteristics of spatial ability

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Purpose: To test spatial ability in athletes with different axial rotation experience and analyze their behavioral data to explain the cognitive mechanisms of spatial ability in athletes.

Methods: Experiment 1: A total of 147 athletes were selected for the paper-and-pencil mental rotation test (MRT). The athletes were separated according to three sport types: open high-spatial (OH) sport, closed high-spatial (CH) sport, closed low-spatial (CL) sport. Spatial ability testing with a two-factor mixed experimental design of 3 (sport type) × 2 (stimulus type). Experiment 2: In this study, 47 players were selected for computerized mental rotation test, with a three-factor mixed experimental design of 3 (sport type) × 2 (angle: 45°, 90°) × 3 (rotational axis: left–right axis, up–down axis, and front–back axis). Repeated-measures ANOVA was performed to evaluate the data.

Results: (1) The CH group and OH group outperformed the CL group in the non-embodied task (all $ps < 0.003$) and the CH group was better than the other groups in the embodied and tasks (all $ps < 0.008$). (2) Under 45° rotational conditions, the reaction time (RT) for the left–right (LR) and up–down (UD) axes were shorter than that for the front-back (FB) axis (all $ps < 0.026$). However, under 90° conditions, the RT for FB < LR < UD, with superior accuracy and rotational speed for the FB axis than for the LR and UD axes (all $ps < 0.034$). (3) Male players from the CH and CL groups had shorter RTs than did those from the OH group at both angles (all $ps < 0.047$). For female players, the CH group presented a shorter RT than the OH and CL groups did at 90° (all $ps < 0.006$). (4) No sex difference was found for paper and pencil MRTs, but a male advantage existed only in the CL group for computerized MRTs ($p = 0.005$).

Conclusion: The motor skills associated with axial rotation could promote mental rotation performance and compensate for sex differences in mental rotation ability.

KEYWORDS

mental rotation, sport type, axial rotation, sex, age

1 Introduction

1.1 Mental rotation

Mental rotation (MR) is a type of intelligence in the spatial cognitive system and refers to the ability to generate, retain, extract, and transform visual images (Wai et al., 2009). Only with good mental rotation ability can we learn and complete precise operations when dealing with complex environments, which is necessary not only in daily life but also in the process of learning and performing movement skills. Therefore, mental rotation is important for the psychological development of elite individuals.

1.1.1 Transformations

Mental rotation consists of two different classes of representations according to the reference frame of rotation: object-based representation and egocentric transformation (Zacks et al., 2002). In the former, subjects perform rotation operations from the third-person perspective, such as watching the leftward movement. In the latter, subjects rotate themselves from a first-person perspective, such as imagining themselves making a leftward turn. According to previous studies, same–different judgments about pairs of pictures are often required for object-based representation and left–right judgments about single pictures for egocentric transformation (Zacks et al., 2000). Voyer et al. (2017) investigated the effect of stimulus type (embodied: hand and non-embodied: letter) on egocentric (left–right judgment) or object-based (same-different judgment) processing in mental rotation and demonstrated that the mental rotation slope for response time was steeper for object-based than for egocentric transformations, verifying different patterns of these two kinds of mental rotation.

1.1.2 Measurement methods

The classical mental rotation test was designed by Shepard and Metzler (1971). Scholars have conducted a variety of experiments based on this paradigm from different perspectives. However, Jansen reported that different measurements can also affect the results (Jansen et al., 2012). Compared with paper and pencil tests, computerized MR tests have been conducted in recent years, which regularly report better performance for men (Debarnot et al., 2013; Peters et al., 2007). Moreover, the number of possible alternatives and whether they are presented as pairwise mirrors are often employed, and a novel study has shown that the overall performance is lower for more alternatives and for mixed alternatives but not for their interaction, suggesting that the differences between tests affect performance (Jost and Jansen, 2023).

1.1.3 Angle effect

As most researchers have shown (Jola and Mast, 2005; Shepard and Metzler, 1971), RTs increase gradually as a function of angular disparity, which means that the more the angle is rotated, the more time the participants are required to react. This may account for the cognitive load at different angles. The cognitive load is one of the factors that influences mental rotation ability (Morawietz and Muehlbauer, 2021). Bennett reported that as the cognitive load increases, participants' accuracy in working memory tasks decreases (Bennett et al., 2013). Studies have confirmed that as interference (i.e., large angular disparity) intensifies, participants' processing of information decreases (Gignac and Vernon, 2003; Bauer et al., 2022).

1.1.4 Individual differences

Studies have suggested that there is at least one sensitive period in the development of adolescents' MR ability (Quaiser-Pohl et al., 2014). MR ability develops rapidly after the age of 10 years and tends to mature around the age of 14–17 years (Doerr et al., 2021; Rahe et al., 2018; He et al., 2019) but gradually decreases with age after the age of 20 years (Borella et al., 2014). In terms of adolescents, middle school students can accurately complete mental rotation tasks (Neuburger et al., 2011). Therefore, adolescent athletes were chosen as the subject of this study.

Additionally, sex differences have been widely studied in the field of MR. Studies have shown that the spatial cognition ability of males is greater than that of females (Hegarty and Waller, 2005). The researchers compared the mental rotation ability of 42 males and 42 females and reported that sex was an effective factor in predicting mental rotation test scores; that is, males had stronger mental rotation ability than females did. One study compared the spatial ability of adolescents with expertise in STEM, arts, and sports with that of their unselected peers to assess sex differences across expert groups. They reported that sex differences persisted in all expert groups (Tsigeman et al., 2023). The reason may be that men are more likely to use the global-shaped strategy and more holistic strategies than women are (Hegarty, 2018). However, when the stimulus type was changed from letter to hand, a reduced male advantage for egocentric rotations compared with object-based rotations was found (Voyer et al., 2017).

1.2 Motor skill learning and mental rotation

1.2.1 Embodied MR for motor experts

As a type of representational operation, mental rotation involves similar cognitive processing to that of real rotation (Wohlschläger and Wohlschläger, 1998). A previous study revealed that the motor areas of the brain are also activated when individuals mentally rotate (Jordan et al., 2002). Therefore, mental rotation ability is closely related to motor expertise (Jost et al., 2023). Some studies have compared the mental rotation ability of individuals with different degrees of sports experience and reported that the mental rotation ability of expert athletes is better than that of ordinary people (Moreau et al., 2015; Schmidt et al., 2015; Moreau et al., 2011). Athletes manipulate and move their bodies in space to practice and improve their skills. Therefore, the advantage for athletes in mental rotation ability after years of training is actually a process of embodiment. In light of embodied cognition, cognitive processing is based on the physical state (Wilson, 2002; Gallese and Sinigaglia, 2011), and all types of cognitive activities, such as thinking, classification and judgment, are not just information processing in the brain but are closely related to one's physical properties, perception, and movement ability.

1.2.2 Sport type

Previous studies have shown that the embodied MR ability of athletes is moderated by sport type. Different sports have different effects on mental rotation ability. Studies have shown that gymnastics and orienteering participants have better mental rotation abilities than soccer and running participants do (Jansen and Lehmann, 2013; Schmidt et al., 2015). Accordingly, it has been further suggested that the stronger the correlation between mental rotation task stimuli and sports experience is, the better the athletes' performance and that the mental rotation ability of athletes in different sports shows "selective influence" (Feng et al., 2017). According to the perspective of action imitation theory, some mental representations and internal mechanisms are shared between motor representations and action execution (Barsalou, 2008). After training, athletes' nervous system

Abbreviations: OH, Open high-spatial sport; CH, Closed high-spatial sport; CL, Closed low-spatial sport; LR, Left–right; UD, Up–down axis; FB, Front-back.

can coordinate with sensory input, thus accelerating the perception of their surroundings and increasing the efficiency of the use of psychological resources (Yin, 2024). However, some studies concerning the spatial essentials of events fail to elucidate the differences between high-spatial sport and low-spatial sport. Sylvie et al. (2002) used two-dimensional cube MRTs to compare sports with high rotation requirements (gymnastics) and low rotation requirements (handball, rugby, basketball, football, badminton, wrestling, judo, track and field), Habacha et al. (2014b) investigated the MR performance of spatial (football, handball, basketball, racket, hockey, gymnastics) and non-spatial (track, wrestling, and swimming) players in three-dimensional MRTs, and Sylvie et al. (2004) examined the MR ability of open sports (rugby, basketball, soccer, badminton, wrestling, judo and tennis) and closed sports (medium distance running, cycling, swimming, gymnastics, archery, javelin, and fitness). However, these methods did not distinguish by different spatial sport types, indicating that the classification method may need to be modified.

1.2.3 Task stimuli

As mentioned previously, stimulus type (i.e., rotation side, direction and angle) can strongly influence the performance of motor experts (Habacha et al., 2014c; Habacha et al., 2014a). Researchers reported that table tennis players made judgments faster on the dominant hand than on the nondominant hand in a mental rotation task (Habacha et al., 2014c). The reactions of gymnasts were faster than those of nonathletes only in their dominant rotation direction (Habacha et al., 2014a). Divers were faster than nonathletes were in judging images at an inverted angle of 180° and showed differences in brain activity (Feng and Li, 2021). In addition, another vital index of rotational movements is the axis. Using the spatial coordinate system as a reference, the axes of human rotation can be divided into the left–right axis, the up–down axis, and the front–back axis. Fargier et al. (2022) compared the MR performance of futsal and rhythmic gymnasts and sedentary people and reported that the reaction time of the football group was shorter in the frontal, horizontal, and sagittal planes than that of the sedentary group, and their reaction time in the horizontal plane was also shorter than that of the rhythmic gymnastics. However, in terms of the MR ability of motor experts with different practices in the rotation axis, whether athletes who are good at rotating their body with multiple axes, such as aerial freestyle skiing athletes, outperform other athletes who often rotate with a single body axis remains unclear.

1.3 The current study

In summary, mental rotation is important for the psychological development of elite individuals, but object-based and egocentric transformations of MR had different patterns of cognitive processing. Individual differences can affect mental rotation ability. Specifically, adolescence is a critical period for the development of mental rotation ability (Doerr et al., 2021; Rahe et al., 2018; He et al., 2019), and males are often considered to have better mental rotation abilities (Hegarty and Waller, 2005). Building on this, from the perspective of embodied cognition, the present study wants to examine the relationship between motor skill learning and spatial ability to address a series of important questions. First, because some studies concerning the spatial essentials of events fail to found the differences between high-spatial sport and low-spatial sport, what role the spatial characteristics of the sport play in the effect of sports experience on mental rotation ability. Can this role of spatial characteristics in sports interact with the stimulus characteristics in mental rotation tasks (such as angle and rotation axis)? In addition to this, can motor skill learning further enhance the mental rotation ability of adolescents, or can it compensate for gender differences in mental rotation ability? Therefore, to investigate the effect of motor expertise type on MR, the spatial factor of sports training, which is coupled with the characteristics of the task stimuli, especially the material angle and axis, should be examined with open-closed types of sports. The present study classifies the spatial sport type via the matrix of high-spatial/low-spatial and open/closed types. According to previous research, closed sports include a stable environment and predictable events (i.e., swimming), but open sports require fast and frequent reactions to unpredictable environmental changes (i.e., basketball) (Sylvie et al., 2004), and high-spatial sports are events that involve mental and physical rotations in their practice (i.e., gymnastics). Low-spatial sports refer to activities that require very little motor rotation (i.e., track and field) (Sylvie et al., 2002). The present study divided three kinds of sport: (1) open high-spatial sport (basketball, soccer, and tennis), (2) closed high-spatial sport (Tai Chi, wrestling, gymnastics, aerobics, aerial freestyle skiing) and (3) closed low-spatial sport (running). Because open sports often involve complex spatial transformation, open low-spatial sports are not defined. Two experiments were conducted to test the influence of axial rotation experience on spatial ability, as well as their interaction with MR transformations, measurement methods and individual differences (age and sex). Experiment 1 used paper and pencil tests to verify the spatial ability differences among the three types of adult athletes, and we hypothesized that the open high-spatial group and the closed high-spatial group would outperform the closed low-spatial group in MRTs with both embodied and non-embodied materials. On this basis, experiment 2 conducts computerized MR tests with egocentric transformations to investigate the spatial ability differences among teenagers in the three types of sports. Similarly, we hypothesized that the open high-spatial and closed high-spatial groups would be superior to the closed low-spatial group and that their advantages would be shown in certain axes or angles congruent with their training experience.

2 Experiment 1

2.1 Participants

A total of 147 participants were enrolled and divided into three groups: (1) open high-spatial sport (OH), which included 50 players from basketball, soccer, and tennis and 26 males and 24 females aged 19 years (68 ± 0.74 years). Their training period was 3.00 ± 2.00 years; (2) closed high-spatial sport (CH), which included 50 players from Tai Chi, wrestling, gymnastics, aerobics, 26 males and 24 females, aged 18.78 ± 1.49 years, and their training period was 2.19 ± 1.49 years; (3) closed low-spatial sport (CL), which included 47 players from running, 28 males and 19 females, aged 19.72 ± 0. 93 years, and their training period was 4.19 ± 2.41 years. A power analysis of the RM ANOVA was conducted with G*Power software using the following settings: expected effect size of 0.25, α-level of 0.05, sample size of 144, and power of 0.99 (1−β). We recruited participants at the Physical Education College of Zhengzhou University and gave their informed consent to participate in this study. None of the participants had completed a mental rotation test before or had been trained in mental rotation.

2.2 Stimuli and task

This study used a modified mental rotation test (MRT) developed by G. Alexander of Texas A&M University (Alexander and Evardone, 2008) to investigate mental rotation ability, as shown in Figure 1. The test contains 24 questions, including 12 original non-embodied (cube) items from the Vandenberg and Kuse (1978) mental rotations test (Peters, 2005), which has been used extensively in the experimental literature on spatial ability. The other 12 embodied (body) figures, constructed via Autodesk Maya 6.5 software, depicted three-dimensional males and females dressed in t-shirts and pants. In three-dimensional space and for the serial positioning of correct items and distracters. Each question has one reference graph and four optional graphs. The participants are required to determine which two of the four options are derived from the rotation of the reference graph. The authors have permission to use this instrument from copyright holders.

2.3 Procedure

The study was conducted in a quiet laboratory room at Henan Sport University on 16 June 2020. Each subject was individually tested. A questionnaire referring to their individual information (including sex, age, exercise level, number of training years, best performance, etc.) was used. Next, they took part in a pencil and paper MRT. The MRT consisted of 24 questions, averaged across four sheets of paper. The instructions for each measure were read aloud, and the participants were provided the same amount before the test began. The participants constructed two practices to ensure that they understood the test and that the practical questions did not appear in the formal test. After the practice period, the participants were asked to choose the two alternatives. As in earlier research (2008), they were asked to complete the first 12 questions in 3 min, followed by a 2-min midway break, and finally, they were asked to complete the last 12 questions. The entire experiment was supervised by two experimenters. Only when the two correct choices of the target figure are correctly selected will the subject receive a point. The participants could score a maximum of 24 points: 12 points for the human body and 12 points for the cube.

2.4 Data analysis

The MR scores for every group obtained a normal distribution ($z < 1.900$, $p > 0.166$, in all instances). Repeated-measures analysis of variance (R-M ANOVA) for MR scores was performed with the between-subject factors of groups (OH, CH, CL) and sex (male, female) and the within-subject factor of stimulus type (cube, body). When the interaction was significant, simple effects analysis was conducted, and the Bonferroni correction method was used for correction. $p < 0.05$ indicates statistical significance, and the partial Eta square (η^2) represents the effect size of the analysis of variance.

2.5 Results

Analysis of the MR score revealed a significant main effect of group, $F\,(1, 141) = 12.532$, $\eta^2 = 0.093$, $p < 0.001$, and stimulus type, $F\,(1, 141) = 14.494$, $p < 0.001$, $\eta^2 = 0.151$, but not for sex, $F\,(2, 141) = 0.005$, $p = 0.945$, $\eta^2 < 0.001$. The interaction effect between group and stimulus type was significant, $F\,(2, 141) = 4.458$, $p = 0.013$, $\eta^2 = 0.059$. Simple effects analysis revealed that in the non-embodied cube task, the OH group (9.92 ± 2.06, 95% CI [9.29, 10.54]) and CH group (10.66 ± 0.96, 95% *CI* [10.03, 11.27]) scored significantly higher than the CL group (8.34 ± 3.12, 95% *CI* [7.74, 9.04], $p < 0.003$, for all instances). In the

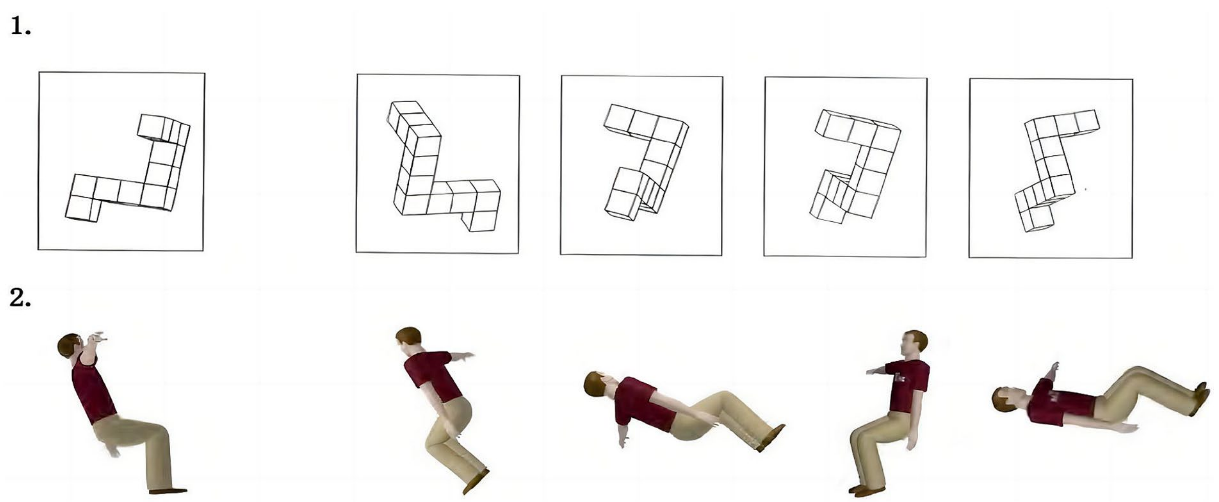

FIGURE 1
Example of the mental rotation test in Experiment 1.

embodied body task, the CH group (11.18 ± 1.00, 95% *CI* [10.63, 11.73]) performed better than did the OH (9.98 ± 1.98, 95% *CI* [9.42, 10.52]) and CL groups (9.55 ± 2.59, 95% *CI* [9.04, 10.19], $p < 0.008$, for all instances). When the scores of stimulus type for each group were compared, the results revealed that only the CL group had different scores between the cube (8.39 ± 3.12, 95% *CI* [7.73, 9.04]) and body tasks (9.62 ± 2.59, 95% *CI* [9.04, 10.19], $p < 0.001$; Figure 2).

2.6 Discussion

In Experiment 1, a classical pen-and-paper assessment was employed to examine disparities in spatial ability among three distinct categories of adult athletes. A total of 147 athletes from open high-spatial sport (basketball, soccer, and tennis), closed high-spatial sport (Tai Chi, wrestling, gymnastics, aerobics) and closed low-spatial sport (running) sports were selected and participated in the experiment. Overall, the results showed that the CH group and OH group outperformed the CL group in the non-embodied task and the CH group was better than the other groups in the embodied and tasks. No sex difference was found for paper and pencil MRTs.

First, differences between the two types of stimuli were confirmed. Embodied cognition suggests that cognitive processing is based on the physical state (Wilson, 2002; Gallese and Sinigaglia, 2011). With respect to mental rotation, body stimuli could facilitate individuals' embodied processing, revealing the common cognitive component between mental rotation and motor rotation; thus, participants in the CL group answered more questions about body stimuli than the cube stimuli. Moreover, the embodied figure task often seems to lead to egocentric transformation of mental rotation (Feng et al., 2017), in which sport expertise facilitates performance because the human body stimulus elicits embodied spatial transformations (Kaltner et al., 2014), even though some studies have suggested that this transformation exists mainly in left–right judgments about single pictures (Zacks et al., 2000).

Concerning the effect of motor expertise on spatial ability, we hypothesize that participants categorized into either the OH group or the CH group are expected to demonstrate superior performance than the CL group on MRTs, irrespective of whether the materials involved are embodied or not embodied. The result showed that the CH group and OH group outperformed the CL group in the non-embodied task and the CH group was better than the other groups in the embodied and tasks. With respect to the result that only the CL group showed different performance between the cube and body tasks, this finding may indicate that sport experience from open skills could ensure the embodiment of body experience in mental rotation. In particular, this effect can be transferred to non-embodied tasks. This may be because open ball sports require athletes to be aware of their teams' and opponents' movements at all times during training and competition, including rotational movements (e.g., basketball and football), which require them to change their strategies and plans on the basis of the change in entrance, thus enhancing their object-based transformation ability and making them more similar to athletes in closed high-spatial sports. This result is consistent with the findings of several studies (Sylvie et al., 2004; Pasand et al., 2015; Habacha et al., 2014b). A study by Jansen et al. (2018) investigated whether increased physical education in schools could enhance mental rotation skills. Adolescents were split into two groups: one receiving extensive physical education and the other receiving a standard amount. Both groups completed questionnaires and took a mental rotation test. The group with more physical education significantly outperformed the control group on the test, indicating that additional physical education training led to improved mental rotation ability.

These findings suggest that it is reasonable to compare the mental rotation ability of high-spatial/low-spatial and open/closed sports. Similar comparisons have been made in previous studies, but differences were not found. In a previous study, athletes were divided into sports with high rotation requirements (gymnastics) and sports with low requirements (i.e., handball, football, basketball), wrestling, judo, and athletics. Similarly, Habacha et al. classified sports into

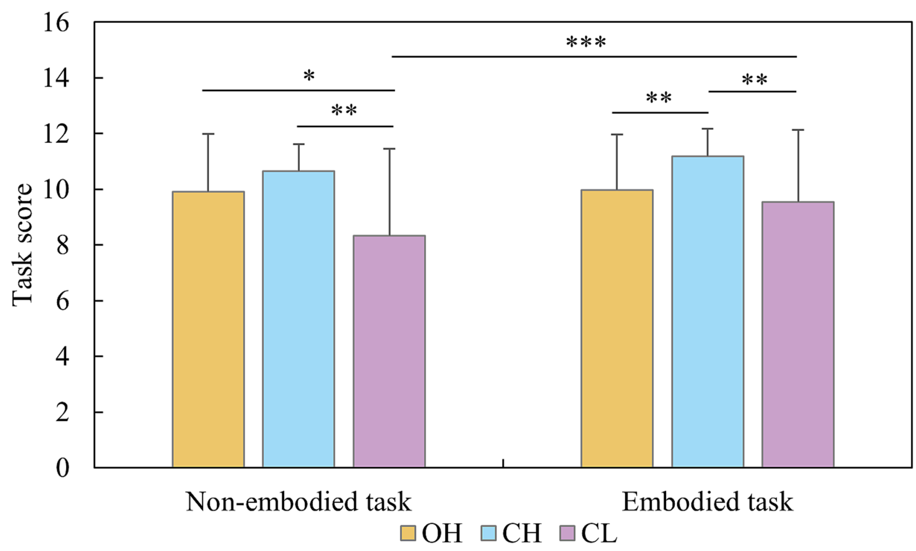

FIGURE 2
Scores on mental rotation tests for different groups and stimulus types (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

spatial (football, handball, basketball, racket sports, hockey, gymnastics) and non-spatial (athletics, wrestling, swimming) sports on the basis of the complexity of spatial factors; however, no differences were found between the groups (Sylvie et al., 2002; Habacha et al., 2014b). There may be two reasons for those results. First, these open high-spatial sports, such as ball games, were treated as non-rotational sports. Second, some closed high-spatial sports, such as wrestling and judo, were also treated as single-axial or non-spatial sports. The results of the study revealed that both closed and open high-spatial sports were able to similarly enhance the mental rotation ability of the athletes.

In addition to sports, sex, an individual factor, has been widely studied in the field of spatial cognition. Studies have shown that the spatial cognition ability of males is greater than that of females (Hegarty and Waller, 2005). However, the effects of motor skill learning on sex differences have not been extensively studied (Voyer and Jansen, 2017). For male and female athletes who have been engaged in sports training for many years and who have similar experience, can sex differences be made up? The conclusions of the current studies are inconsistent. From the perspective of cognitive plasticity, researchers believe that a sex difference between male and female athletes already exists and that the gap between the two is different in the process of accumulating sports experience. Therefore, even if they both have sports experience, a sex gap still exists (Pietsch and Jansen, 2012; Schmidt et al., 2015; Fargier et al., 2022). In contrast, some studies believe that female athletes can achieve greater improvements in activities; that is, sex differences can be compensated for by participation in physical activities (Habacha et al., 2014b). Therefore, the present study investigated the influence of sex on players' mental rotation, and no sex difference was found within either group or task type, which supported the latter opinion.

3 Experiment 2

3.1 Participants

The study population, comprising 46 people, was divided into three groups on the basis of the type of sport: (1) an open high-spatial sport (OH) group consisting of 16 basketball and soccer players (8 males and 8 females) who were 13.31 ± 0.79 years old and had 2.23 ± 1.43 training years. (2) a closed high-spatial sport (CH) group consisting of 15 freestyle skiing players (8 males and 7 females) who were 14.60 ± 1.02 years old and had 3 ± 0.34 training years; and (3) a closed low-spatial sport (CL) group consisting of 15 runners (9 males and 6 females) who were 14.60 ± 1.78 years old and had a training time of 1.27 ± 0.44 years.

3.2 Task stimuli

The experimental stimuli were body movement pictures designed with ArtPose software, which consisted of a picture of a male with one arm raised upward and the other arm raised sideways. Only one figure is presented at a time, and the subject needs to choose which arm was, according to the axial characteristics of the movement, three types of rotation are distinguished: (1) rotation around the left–right (LR) axis of the body. (2) Rotation around the up–down (UD) axis of the body. (3) Rotation around the front-back (FB) axis of the body. The rotation angle of each axial direction includes a small angle (45°) and a large angle (90°), as shown in Figure 3. The image size is 700 × 900 pixels. The experimental task was designed with E-Prim 3.0 (Psychology Software Tools, www.pstnet.com) and presented using a 23.8-inch computer.

3.3 Procedure

The experiment was conducted in the laboratory of Henan Sport University, and each subject was tested separately in a closed, quiet, noninterference environment. After the purpose and operation of the experiment were explained, the participants were seated in front of the computer (the eyes were 60 cm away from the screen). The experimental data were prepared via E-Prime 3.0 software. There were six stimulus conditions (left–right axis at a small angle, left–right axis at a large angle, up–down axis at a small angle, up–down axis at a large angle, front-back axis at a small angle, and front-back axis at a large angle). First, all participants attended a practice part with 10 experimental trials. In each trial, 500 ~ 800 ms of fixation occurred in the middle of the screen, after which a stimulus picture was presented. The subjects were required to determine whether the man in the picture was raising up his left arm (press key "F") or the right arm (press key "J") accurately and quickly. The picture disappeared after the button or time exceeded 4,000 ms, and a feedback screen (showing "right" or "wrong") was presented for 500 ms before the next trial. Responses submitted more than 4,000 ms after presentation of the stimulus were considered as errors. The stimulus in practice part included pictures with all combines of axis and angle. The practice accuracy of every subject had to be above 80% to ensure that they had completely understood the task. Two subjects practiced twice to reach the criterion. Second, the formal experiment used similar test trials in practice but did not give feedback. The formal experiment contained three same blocks, each containing 90 randomly ordered trials (for 6 stimulus conditions × 15 repetition). Each subject rested for 10 s before moving on to the next block until all three blocks were completed. The response time and accuracy were obtained. The overall duration of the experiment was approximately 20 min (Figure 4).

3.4 Data analysis

The reaction time (RT), accuracy and stage performance were calculated for every group. According to the phases of information processing, mental rotation is subdivided into the perceptual stage, rotation stage, and decision stage (Heil and Rolke, 2002; Shepard and Cooper, 1982; Corballis, 1988). Specifically, the performance in the perceptual and decision stages is the RT when the stimulus is not rotated, and the mental rotation speed represents the performance of the rotation stage. In the present study, the rotation speed was used as the performance of the rotation stage and was the average of the ratio of the angle at each angle to the RT. The calculation formula is $\text{rotational speed} = \left(\frac{45}{RT_{45°}} + \frac{90}{RT_{90°}} \right) \div 2 \times 1000$, where the unit is represented in degrees per second (°/s). The perceptual time was subsequently

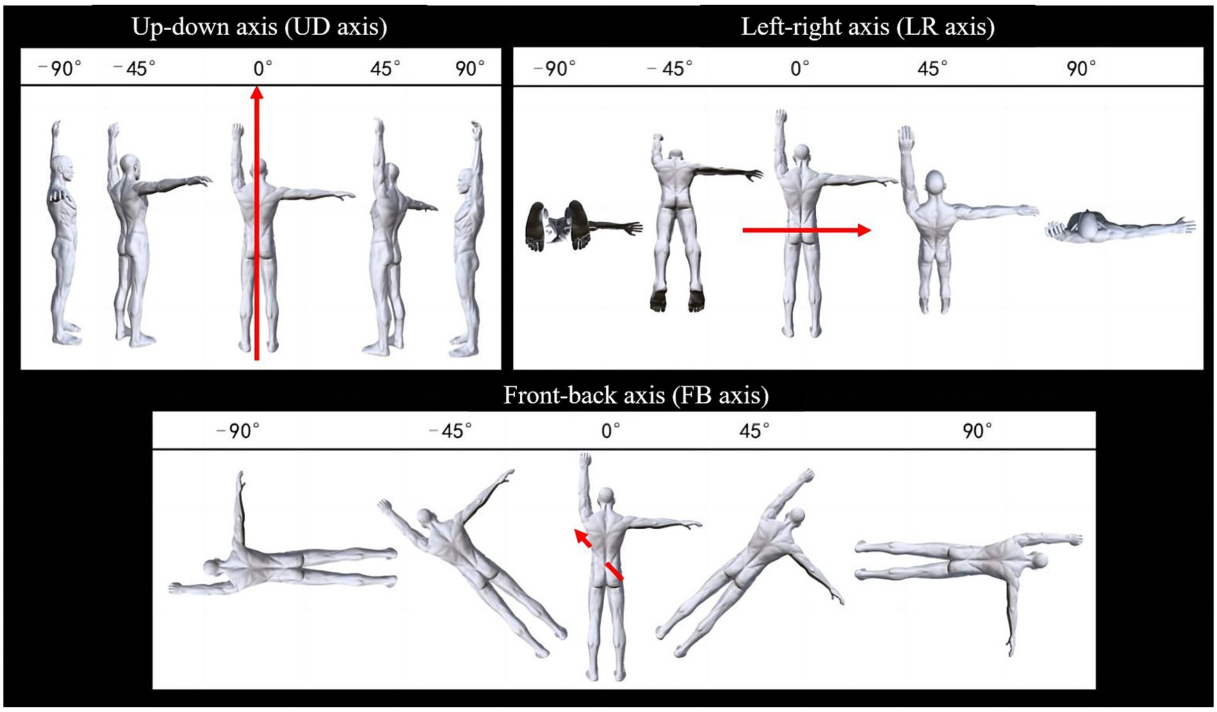

FIGURE 3
Example of the stimuli used in Experiment 2.

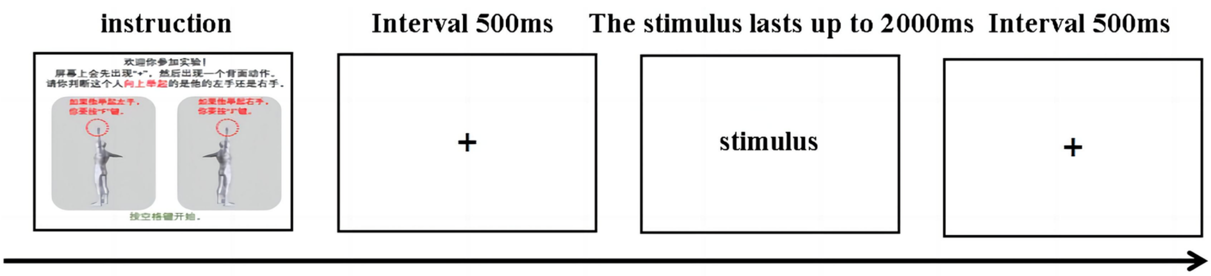

FIGURE 4
Mental rotation task in Experiment 2.

calculated via the following formula: RT = perceptual time + angle*rotational speed. Normal distributions were obtained for all variables ($z < 1.166$, $p > 0.132$, in all instances). With respect to RT and accuracy, four-factor R-M ANOVA was conducted with the between-subject factors of group (OH, CH, CL) and sex (male, female) and the within-subject factors of the rotational axis (left–right (LR) axis, up–down (UD) axis, and front–back (FB) axis) and angle (45°, 90°). For stage performance, three-factor R–M ANOVA was conducted with the between-subject factors of group (OH, CH, CL) and sex (male, female) and the within-subject factors of the rotational axis (left–right (LR) axis, up–down (UD) axis, and front–back (FB) axis). Simple effects analysis was conducted when the interaction was significant, and the Bonferroni correction method was used for correction. $p < 0.05$ indicates statistical significance, and the partial Eta square (η^2) represents the effect size of the analysis of variance.

3.5 Results

3.5.1 Reaction time

ANOVA revealed significant main effects for group, F (2, 40) = 9.382, $p < 0.001$, $\eta^2 = 0.362$; rotational axis, F (2, 80) = 7.582, $p < 0.001$, $\eta^2 = 0.187$; and angle, F (1, 40) = 265.224, $p < 0.001$, $\eta^2 = 0.889$. The interaction effects for group and angle, F (1, 40) = 7.225, $p = 0.002$, $\eta^2 = 0.305$; sex and angle, F (1, 40) = 6.449, $p = 0.016$, $\eta^2 = 0.163$; and rotational axis and angle, F (2, 80) = 40.151, $p < 0.001$, $\eta^2 = 0.549$, were significant. Additionally, the three-way interaction of group, sex and angle was significant, F (2, 40) = 4.385, $p = 0.020$, $\eta^2 = 0.210$. Simple effects analysis revealed that male players in the OH group (45° *CI*: 671.76 ± 178.21, 95% *CI* [571.65, 771.88], 90° *CI*: 855.09 ± 129.81, 95% *CI* [728.36, 981.82]) had longer RTs than did those in the CH (45° *CI*: 474.80 ± 69.53, 95% *CI* [404.1, 545.59], 90° *CI*: 655.52 ± 85.73, 95% *CI* [565.91, 745.13]) and CL

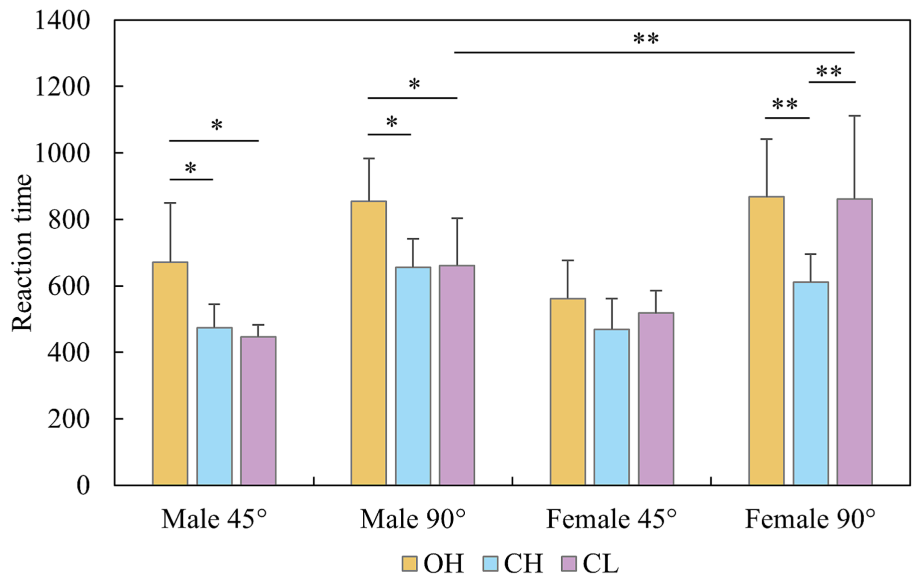

FIGURE 5
Reaction time of the mental rotation task for group, sex, and angle.

groups (45° *CI*: 446.97 ± 35.95, 95% *CI* [376.18, 517.76], 90° *CI*: 660.53 ± 143.60, 95% *CI* [570.92, 750.14]) at both angles ($p < 0.047$, for all instances). For female players, the CH group presented a shorter RT than the OH and CL groups did at 90° ($p < 0.006$, for all instances). The OH (867.45 ± 174.42, 95% *CI* [763.97, 970.92]) and CL (861.46 ± 249.52, 95% *CI* [757.99, 964.93]) groups presented longer RTs than did the CH (610.77 ± 84.10, 95% *CI* [514.97, 706.57]) group at 90° ($p < 0.002$, for all instances). Moreover, males (660.53 ± 143.60, 95% *CI* [570.92, 750.14]) demonstrated faster RT than females did (861.46 ± 249.52, 95% *CI* [757.99, 964.93]) at 90° in the CL group ($p = 0.005$). The difference in RT for two angles was significant for every group, axis and sex ($p < 0.001$, for all instances). Interestingly, under 45° conditions, the RT for the LR (508.07 ± 155.28, 95% *CI* [463.10, 553.13]) and UD axes (505.80 ± 106.43, 95% *CI* [474.63, 536.97]) was shorter than that for the FB axis (557.22 ± 114.42, 95% *CI* [521.32, 593.11], $p < 0.026$, for all instances), but under 90° conditions, the RT for the FB axis (660.85 ± 122.48, 95% *CI* [625.82, 695.87]) < LR (756.64 ± 207.49, 95% *CI* [695.33, 817.96]) < UD axis (837.92 ± 207.63, 95% *CI* [785.09, 890.75], $p < 0.034$, for all instances; Figures 5, 6).

3.5.2 Accuracy

ANOVA revealed significant main effects of the rotational axis, F (2, 80) = 6.891, $p = 0.002$, $\eta^2 = 0.187$, and angle, F (1, 40) = 41.577, $p < 0.001$, $\eta^2 = 0.581$. The interaction between the rotational axis and angle was significant, F (2, 80) = 9.914, $p < 0.001$, $\eta^2 = 0.248$. The simple effects analysis revealed that the accuracy at 45° was better than that at 90° for the LR (0.993 ± 0.016, 95% *CI* [0.986, 0.998]) and UD axes (0.980 ± 0.025, 95% *CI* [0.966, 0.994]] but not for the FB axis (0.983 ± 0.018, 95% *CI* [0.976, 0.990], $p < 0.022$, for all instances). Additionally, all the players' accuracy for the FB axis (0.986 ± 0.015, 95% *CI* [0.980, 0.991]) were superior to those for the LR (0.954 ± 0.059, 95% *CI* [0.927, 0.968]) and UD (0.943 ± 0.049, 95% *CI* [0.925, 0.961]) axes at the 90° ($p < 0.032$, for all instances; Figure 7).

3.5.3 Stage performance

For rotational speed, ANOVA revealed a significant main effect of the rotational axis, F (2, 80) = 7.209, $p = 0.002$, $\eta^2 = 0.199$, indicating that participants mentally rotated faster for the FB axis (696.77 ± 466.47, 95% *CI* [404.33, 885.27]) than for the UD axis (169.28 ± 86.30, 95% *CI* [124.66, 193.43], $p = 0.018$). The results for the perceptual time revealed a significant main effect of the rotational axis, F (2, 80) = 23.809, $p < 0.001$, $\eta^2 = 0.488$, indicating that participants took less time to recognize the stimuli for the LR (301.25 ± 216.54, 95% *CI* [223.87, 378.63]) and UD (217.20 ± 131.23, 95% *CI* [165.73, 268.66]) axes than for the FB axis (456.32 ± 155.81, 95% *CI* [397.84, 514.80], $p < 0.001$).

3.6 Discussion

In experiment 2, a three-dimensional computerized egocentric MRT with different rotation angles (45°, 90°) was used to test the spatial ability of adolescent athletes in different sport types (open high-spatial sport, closed high-spatial sport and closed low-spatial sport). In general, the results found that under 45° rotational conditions, the reaction time (RT) for the left–right (LR) and up–down (UD) axes were shorter than that for the front-back (FB) axis. Nevertheless, under 90° conditions, the RT for FB < LR < UD, with superior accuracy and rotational speed for the FB axis than for the LR and UD axes. Concerning the effect of gender, male players from the CH and CL groups had shorter RTs than did those from the OH group at both angles. For female players, the CH group presented a shorter RT than the OH and CL groups did at 90°.

The angle effect was confirmed by the result showing that the RT of the large-angle (90°) mental rotation test was significantly longer than that of the small-angle (45°) mental rotation test, and the accuracy of the small-angle test was significantly shorter than that of the large-angle test for the LR and UD axes. This finding is consistent

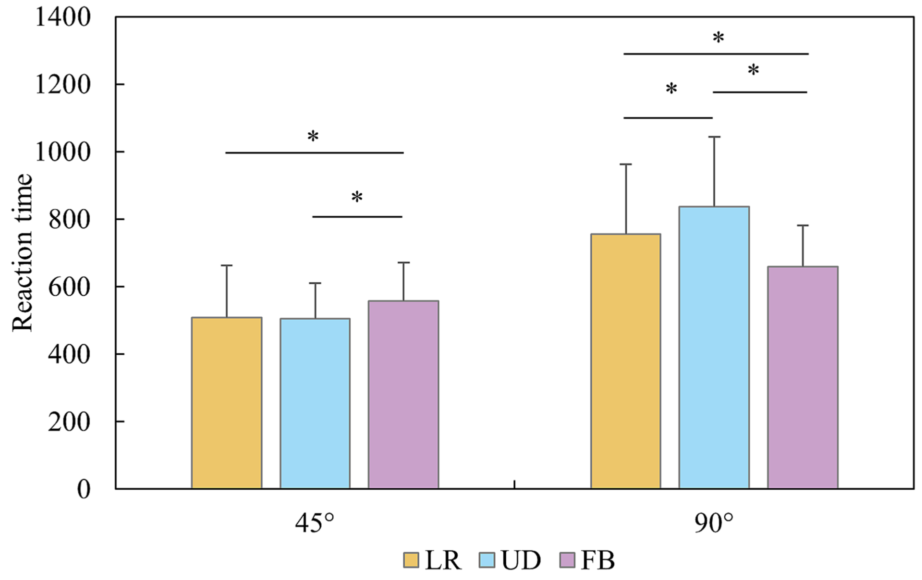

FIGURE 6
Reaction time of the mental rotation task for axis and angle.

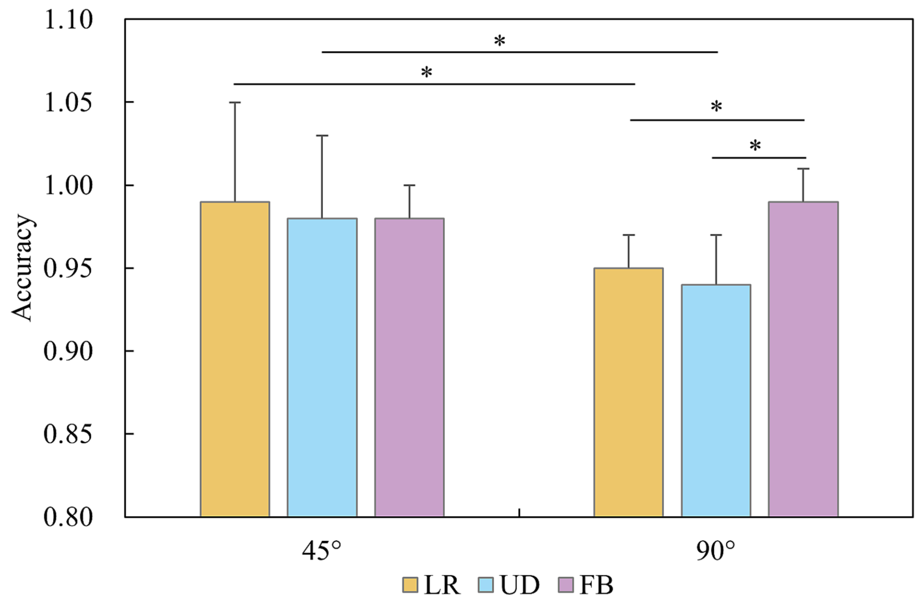

FIGURE 7
Accuracy of the mental rotation task for group and angle.

with the study by Bethell-Fox et al., who reported that as the difficulty of the stimulating material increased, the subjects' responses to the mental rotation test increased (Bethell-Fox and Shepard, 1988). An increase in the rotation angle is clearly associated with an increase in difficulty, suggesting that better mental rotation ability is required for athletes to perform more difficult mental rotation tests and consume more cognitive resources (Zhao et al., 2022).

In terms of the rotation axis, most previous studies carried out paper-plane rotation (i.e., the FB axis in the present study). To scrutinize the MR differences among the three rotational axes in athletes, a study compared the performance of futsal players, rhythmic gymnasts, and sedentary individuals on mental rotation tasks. The research revealed that futsal players had quicker reaction times across all tested planes—frontal, horizontal, and sagittal—than did sedentary players. Notably, their reaction times in the horizontal plane were also faster than those of the rhythmic gymnasts (Fargier et al., 2022). Habacha et al. (2014a) reported that gymnasts were faster than nonathletes in their dominant rotation direction. However, the present study did not find an interaction between sport group and axis. The results demonstrated different mechanisms at different angles. In particular, under 45° rotational conditions, the RT for the LR and UD axes was shorter than that for the FB axis. However, under 90° conditions, the RT for FB < LR < UD, with superior accuracy and rotational speed for the FB axis than for the LR and UD axes. Therefore, when the body rotated a small angle around the UD and LR axes, the postures looked very similar to the standing posture, thus yielding faster RT and perceptual time. However, after large-angle rotation of the body around the UD and LR axes, some body parts were sheltered (i.e., we cannot see the right arm in the 90° UD condition, as well as the feet in the 90° LR condition, see Figure 3), thus increasing the difficulty of the task. In contrast, regardless of the angle at which the body rotates around the FB axis, the body will not be sheltered due to the rotation action, so the results revealed a faster RT and perception speed of the FB axis at a large angle.

After dividing the players into three groups with various spatial characteristics, we investigated the effects of spatial motor experience on mental rotation at small and large angles. Male players from the CH and CL groups had shorter RTs than did those from the OH group at both angles. For female players, the CH group presented a shorter RT than the OH and CL groups did at 90°. The interactions among sport type, sex and angle are very meaningful. According to earlier studies, the CH group should show a significant advantage for MR over the other groups (Jansen and Lehmann, 2013; Schmidt et al., 2015; Feng et al., 2017), which is congruent with our results in females. Nevertheless, how do male players from the CL group, such as runners, obtain better MR ability than those from the OH group, such as basketball and soccer players, and similar MR ability to that of the CH group, such as freestyle skiing players? There are two explanations below. First, the MR for male individuals may benefit much more from sport training, even for closed low-spatial-level sports such as running. Influencing factors may be associated with individual physiological factors such as genetics, lateralization of brain function, sex hormones, and brain size (Siegel-Hinson and McKeever, 2002; Peters et al., 2007). Second, attending sports may lead to better mental rotation ability for boys. A study reported a positive relationship between motor ability and accuracy on mental rotation tasks among primary school-aged and young children (Jansen and Kellner, 2015; Jansen and Heil, 2010).

4 General discussion

This study explored the effects of axial rotation on the spatial ability of athletes through two experiments. In Experiment 1, a paper and pencil mental rotation test was conducted, and it was found that the CH group performed better than the other groups did in both embodied and non-embodied tasks, which supported our hypothesis, indicating that skilled sports (i.e., Tai Chi, wrestling, gymnastics, aerobics) have the most significant effects on mental rotation. Moreover, this advantage for the adolescent CH group was also revealed by the computerized MRT in experiment 2, supporting the view of embodiment cognition that all types of cognitive activities are closely related to one's ability to move the body (Wilson, 2002; Gallese and Sinigaglia, 2011).

Sex and age can affect MR ability. Some studies have shown that sex differences in mental-rotation performance are significant for children under age 13 and increase during adolescence (Voyer, 1995) and sex differences persist in all expert groups, such as STEM, arts, and sports (Tsigeman et al., 2023). Other studies suggest that female athletes can achieve greater improvements in activities; that is, sex differences can be compensated for by participation in physical activities (Habacha et al., 2014b). Researchers believe that women can more significantly modify their visual search behavior during activity participation and thus perform better in the perceptual process or the encoding process of the mental rotation task (Jansen et al., 2012) to increase their mental rotation score. Can the enhancement of mental rotation ability caused by sports activities compensate for the gender differences in mental rotation ability among adolescents? The present study found no sex difference in adolescents' mental rotation performance for paper and pencil MRTs (in experiment 1), but confirmed a male advantage only in the CL group for computerized MRTs (in experiment 2).

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This result offers at least two insights. First, the testing method of mental rotation indeed influences the appearance of gender differences. Compared with computerized MRT, paper-and-pencil testing tends to have less time pressure (Peters, 2005). Under these circumstances, females who participate in sports may receive similar scores to those of males because females can fully understand the questions and effectively manage their time. Second, in Experiment 2, gender differences were observed only in the CL group but not in the other groups, indicating that the spatial characteristics of motor skills can affect gender differences in mental rotation. Specifically, in sports with high spatial transformation (whether open or closed), there was no difference in mental rotation ability between males and females, suggesting that females indeed gain more enhancement during the learning of spatial sports (such as basketball, soccer, gymnastics, etc.). This finding is important for explaining how motor skills influence gender differences in mental rotation and it has certain practical significance. For adolescents, to enhance spatial ability and thereby improve STEM performance, participating in sports with rich spatial transformation in daily physical exercise, school physical education courses, and specialized sports training is a better choice.

The study also has certain limitations. First, concerning the classification of sports, the present study made an initial attempt to categorize sports on the basis of their spatial characteristics. However, the number of sports included in each type of sports project is relatively small. Future research should include more sports of the same type for comparison. Second, with the advancement of cognitive neuroscience, the relationship between motor skills and mental rotation ability can now be explored within the field of brain plasticity. For example, if spatial sports training indeed leads to greater improvements in mental rotation ability for females, it is necessary to determine whether this process is due to differences in brain processing (Feng and Li, 2021; Yin, 2024). To address this question, more studies utilizing electroencephalography (EEG) or functional near-infrared spectroscopy (fNIRS) technology are needed.

5 Conclusion

The present study utilized spatial factors and sex to assess the mental rotation ability of adult and adolescent athletes and, for the first time, confirmed the role of the rotational axis in the relationship between sport expertise and mental rotation in light of embodied cognition. The results showed that the CH group and OH group outperformed the CL group in the non-embodied task and the CH group was better than the other groups in the embodied and tasks. Under 45° rotational conditions, the RT for the LR and UD axes was shorter than that for the FB axis. However, under 90° conditions, the RT for FB < LR < UD, with superior accuracy and rotational speed for the FB axis than for the LR and UD axes. Male players from the CH and CL groups had shorter RTs than did those from the OH group at both angles. For female players, the CH group presented a shorter RT than the OH and CL groups did at 90°. No sex difference was found for paper and pencil MRTs, and a male advantage existed only in the CL group for computerized MRTs. These results suggest that the motor skills associated with axial rotation could promote MR performance and compensate for sex differences in MR ability.

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 Physical Education College of Zhengzhou 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

YL: Conceptualization, Investigation, Methodology, Software, Supervision, Writing – review & editing. TF: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. FZ: Data curation, Formal analysis, Methodology, Project administration, Supervision, Writing – review & editing. JL: Data curation, Formal analysis, Methodology, Software, Supervision, Writing – original draft, Writing – review & editing. ML: Data curation, Formal analysis, Methodology, Project administration, Supervision, Writing – review & editing.

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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.2024.1396441/full#supplementary-material

References

Alexander, G. M., and Evardone, M. (2008). Blocks and bodies: sex differences in a novel version of the mental rotations test. *Horm. Behav.* 53, 177–184. doi: 10.1016/j.yhbeh.2007.09.014

Barsalou, L. W. (2008). Grounded cognition. *Annu. Rev. Psychol.* 59, 617–645. doi: 10.1146/annurev.psych.59.103006.093639

Bauer, R., Jost, L., Gunther, B., and Jansen, P. (2022). Pupillometry as a measure of cognitive load in mental rotation tasks with abstract and embodied figures. *Psychol. Res.* 86, 1382–1396. doi: 10.1007/s00426-021-01568-5

Bennett, I. J., Rivera, H. G., and Rypma, B. (2013). Isolating age-group differences in working memory load-related neural activity: assessing the contribution of working memory capacity using a partial-trial fmri method. *NeuroImage* 72, 20–32. doi: 10.1016/j.neuroimage.2013.01.030

Bethell-Fox, C. E., and Shepard, R. N. (1988). Mental rotation: effects of stimulus complexity and familiarity. *J. Exp. Psychol. Hum. Percept. Perform.* 14, 12–23. doi: 10.1037/0096-1523.14.1.12

Borella, E., Meneghetti, C., Ronconi, L., and De Beni, R. (2014). Spatial abilities across the adult life span. *Dev. Psychol.* 50, 384–392. doi: 10.1037/a0033818

Corballis, M. C. (1988). Recognition of disoriented shapes. *Psychol. Rev.* 95, 115–123. doi: 10.1037/0033-295X.95.1.115

Debarnot, U., Piolino, P., Baron, J. C., and Guillot, A. (2013). Mental rotation: effects of gender, training and sleep con-solidation. *PLoS One* 8:e60296. doi: 10.1371/journal.pone.0060296

Doerr, E. M., Carretti, B., Toffalini, E., Lanfranchi, S., and Meneghetti, C. (2021). Developmental trajectories in spatial visualization and mental rotation in individuals with down syndrome. *Brain Sci.* 11:610. doi: 10.3390/brainsci11050610

Fargier, P., Champely, S., Massarelli, R., Ammary, L., and Hoyek, N. (2022). Modelling response time in a mental rotation task by gender, physical activity, and task features. *Sci. Rep.* 12:15559. doi: 10.1038/s41598-022-19054-2

Feng, T., and Li, Y. (2021). The time course of event-related brain potentials in athletes' mental rotation with different spatial transformations. *Front. Behav. Neurosci.* 15:675446. doi: 10.3389/fnbeh.2021.675446

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

Gallese, V., and Sinigaglia, C. (2011). What is so special about embodied simulation? *Trends Cogn. Sci.* 15, 512–519. doi: 10.1016/j.tics.2011.09.003

Gignac, G., and Vernon, P. A. (2003). Digit symbol rotation: a more g-loaded version of the traditional digit symbol subtest. *Intelligence* 31, 1–8. doi: 10.1016/S0160-2896(02)00118-6

Habacha, H., Lejeune-Poutrain, L., Margas, N., and Molinaro, C. (2014a). Effects of the axis of rotation and primordially solicited limb of high level athletes in a mental rotation task. *Hum. Mov. Sci.* 37, 58–68. doi: 10.1016/j.humov.2014.06.002

Habacha, H., Molinaro, C., and Dosseville, F. (2014b). Effects of gender, imagery ability, and sports practice on the performance of a mental rotation task. *Am. J. Psychol.* 127, 313–323. doi: 10.5406/amerjpsyc.127.3.0313

Habacha, H., Molinaro, C., Tabben, M., and Lejeune-Poutrain, L. (2014c). Implementation of specific motor expertise during a mental rotation task of hands. *Exp. Brain Res.* 232, 3465–3473. doi: 10.1007/s00221-014-4029-3

He, Z.-H., Li, B.-H., and Yin, W.-G. (2019). Executive function and mental rotation during middle childhood: the effect of age. *J. Genet. Psychol.* 180, 96–102. doi: 10.1080/00221325.2019.1582474

Hegarty, M. (2018). Ability and sex differences in spatial thinking: what does the mental rotation test really measure? *Psychonom. Bullet. Rev.* 25, 1212–1219. doi: 10.3758/s13423-017-1347-z

Hegarty, M., and Waller, D. (2005). "Individual differences in spatial abilities" in The Cambridge handbook of visuospatial thinking. New York, NY: Cambridge University Press, 121–169.

Heil, M., and Rolke, B. (2002). Toward a chronopsychophysiology of mental rotation. *Psychophysiology* 39, 414–422. doi: 10.1111/1469-8986.3940414

Jansen, P., Ellinger, J., and Lehmann, J. (2018). Increased physical education at school improves the visual-spatial cognition during adolescence. *Educ. Psychol.* 38, 964–976. doi: 10.1080/01443410.2018.1457777

Jansen, P., and Heil, M. (2010). The relation between motor development and mental rotation ability in 5- to 6-year-old children. *Eur. J. Dev. Sci.* 4, 66–74. doi: 10.1088/0370-1298/64/10/117

Jansen, P., and Kellner, J. (2015). The role of rotational hand movements and general motor ability in children's mental rotation performance. *Front. Psychol.* 6:984. doi: 10.3389/fpsyg.2015.00984

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

Jola, C., and Mast, F. (2005). Mental object rotation and egocentric body transformation: two dissociable processes? *Spat. Cogn. Comput.* 5, 217–237. doi: 10.1207/s15427633scc052&3_6

Jordan, K., Wüstenberg, T., Heinze, H.-J., Peters, M., and Jäncke, L. (2002). Women and men exhibit different cortical activation patterns during mental rotation tasks. *Neuropsychologia* 40, 2397–2408. doi: 10.1016/S0028-3932(02)00076-3

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. *Q. J. Exp. Psychol.* 77, 1250–1271. doi: 10.1177/17470218231200127

Jost, L., Weishäupl, A., and Jansen, P. (2023). Interactions between simultaneous aerobic exercise and mental rotation. *Curr. Psychol.* 42, 4682–4695. doi: 10.1007/s12144-021-01785-6

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

Morawietz, C., and Muehlbauer, T. (2021). Effects of physical exercise interventions on spatial orientation in children and adolescents: a systematic scoping review. *Front. Sports Act. Living* 3:664640. doi: 10.3389/fspor.2021.664640

Moreau, D., Clerc, J., Mansy-Dannay, A., and Guerrien, A. (2011). Spatial ability and motor performance: assessing mental rotation processes in elite and novice athletes. *Int. J. Sport Psychol.* 54, 167–179.

Moreau, D., Morrison, A. B., and Conway, A. R. A. (2015). An ecological approach to cognitive enhancement: complex motor training. *Acta Psychol.* 157, 44–55. doi: 10.1016/j.actpsy.2015.02.007

Neuburger, S., Jansen, P., Heil, M., and Quaiser-Pohl, C. (2011). Gender differences in pre-adolescents' mental-rotation performance: do they depend on grade and stimulus type? *Personal. Individ. Differ.* 50, 1238–1242. doi: 10.1016/j.paid.2011.02.017

Pasand, F., Rekabi, A., Goodarzi, A. M., and Chahardahcheric, M. (2015). The comparison of mental rotation performance in team and individual sports of students. *Int. J. Kinesiol. Sports Sci.* 3, 21–26. doi: 10.7575/aiac.ijkss.v.3n.1p.21

Peters, M. (2005). Sex differences and the factor of time in solving Vandenberg and Kuse mental rotation problems. *Brain Cogn.* 57, 176–184. doi: 10.1016/j.bandc.2004.08.052

Peters, M., Manning, J. T., and Reimers, S. (2007). The effects of sex, sexual orientation, and digit ratio (2D:4D) on mental rotation performance. *Arch. Sex. Behav.* 36, 251–260. doi: 10.1007/s10508-006-9166-8

Pietsch, S., and Jansen, P. (2012). "The relationship between coordination skill and mental rotation ability" in *Proceedings of the 2012 international conference on Spatial Cognition VIII*. eds. C. Stachniss, K. Schill and D. Uttal (Berlin: Springer), 173–181.

Quaiser-Pohl, C., Neuburger, S., Heil, M., Jansen, P., and Schmelter, A. (2014). Is the male advantage in mental-rotation performance task independent? On the usability of chronometric tests and paper-and-pencil tests in children. *Int. J. Test.* 14, 122–142. doi: 10.1080/15305058.2013.860148

Rahe, M., Ruthsatz, V., Jansen, P., and Quaiser-Pohl, C. (2018). Influence of sex-stereotyped stimuli on the mental-rotation performance of elderly persons. *Exp. Aging Res.* 44, 284–296. doi: 10.1080/0361073X.2018.1475156

Schmidt, M., Egger, F., Kieliger, M., Rubeli, B., and Schüler, J. (2015). Gymnasts and orienteers display better mental rotation performance than non-athletes. *J. Individ. Differ.* 37, 1–7. doi: 10.1027/1614-0001/a000180

Shepard, R. N., and Cooper, L. A. (1982). Mental images and their transformations. Cambridge, MA: Mit Press.

Shepard, R. N., and Metzler, J. (1971). Mental rotation of three-dimensional objects abstract. *Science* 171, 701–703. doi: 10.1126/science.171.3972.701

Siegel-Hinson, R. I., and Mckeever, W. F. (2002). Hemispheric specialisation, spatial activity experience, and sex differences on tests of mental rotation ability. *Laterality* 7, 59–74. doi: 10.1080/13576500143000078

Sylvie, O., Jacques, L., and Molinaro, C. (2004). Relation between sport and spatial imagery: comparison of three groups of participants. *J. Psychol.* 138, 49–64. doi: 10.3200/JRLP.138.1.49-64

Sylvie, O., Larue, J., and Molinaro, C. (2002). Relation between sport activity and mental rotation: comparison of three groups of subjects. *Percept. Mot. Skills* 95, 1141–1151. doi: 10.2466/pms.2002.95.3f.1141

Tsigeman, E. S., Likhanov, M. V., Budakova, A. V., Akmalov, A., Sabitov, I., Alenina, E., et al. (2023). Persistent gender differences in spatial ability, even in Stem experts. *Heliyon* 9:e15247. doi: 10.1016/j.heliyon.2023.e15247

Vandenberg, S. G., and Kuse, A. R. (1978). Mental rotation, a group test of three-dimensional spatial visualization. *Percept. Mot. Ski.* 47:599–604. doi: 10.2466/pms.1978.47.2.599

Voyer, D. (1995). Magnitude of sex differences in spatial abilities. *Psychol. Bull.* 117, 250–270. doi: 10.1037/0033-2909.117.2.250

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

Voyer, D., Jansen, P., and Kaltner, S. (2017). Mental rotation with egocentric and object-based transformations. *Q. J. Exp. Psychol.* 70, 2319–2330. doi: 10.1080/17470218.2016.1233571

Wai, J., Lubinski, D., and Benbow, C. P. (2009). Spatial ability for Stem domains: aligning over 50 years of cumulative psychological knowledge solidifies its importance. *J. Educ. Psychol.* 101, 817–835. doi: 10.1037/a0016127

Wilson, M. (2002). Six views of embodied cognition. *Psychon. Bull. Rev.* 9, 625–636. doi: 10.3758/BF03196322

Wohlschläger, A., and Wohlschläger, A. (1998). Mental and manual rotation. *J. Exp. Psychol. Hum. Percept. Perform.* 24, 397–412. doi: 10.1037/0096-1523.24.2.397

Yin, C. (2024). Differences in spatial perception of football players: studies based on behavioral and fnirs (in Chinese). *J. Phys. Educ.* 31, 143–148.

Zacks, J. M., Mires, J., Tversky, B., and Hazeltine, E. (2000). Mental spatial transformations of objects and perspective. *Spat. Cogn. Comput.* 2, 315–332. doi: 10.1023/A:1015584100204

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

Zhao, M., Liu, J., Bao, S., and Liu, Y. (2022). The influence of task difficulty on orienteering practitioners' route decision-making: evidence from fnirs. (in Chinese) *J. Shandong Phys. Educ. Inst.* 38, 110–118.

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Effects of mindfulness intervention on competition state anxiety in sprinters—a randomized controlled trial

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Objectives: With the rapid growth of China's sprint program's international competitiveness, the psychological problems of sprinters have become a common concern in sports training theory and practice. Hence, the study examined the impact of a 7-week Mindfulness training program on competition state anxiety in Chinese sprinters.

Methods: Twenty-four sprinters ($M_{age} = 22.46 \pm 1.351$) were selected in a 2 × 3 mixed design, with the group (mindfulness/control) as the between-subjects variable and test time (pre-test/mid-test/post-test) as the within-subjects variable. The dependent variables corresponded to the mindfulness score and competition state anxiety score. One 60-min session was conducted once a week for 7 weeks, and the control group did not undergo any psychological training. The mindfulness group received mindfulness training, and the control group received regular psychological guidance. The subjects filled in the Five Facet Mindfulness Questionnaire (FFMQ) and the Competition State Anxiety Scale at baseline, followed by additional assessments 3 weeks and 7 weeks later.

Results: (1) In terms of competition state anxiety, there were no significant differences in the pre-test between the mindfulness group and the control group. There were significant differences in sprinters' competition state anxiety after mindfulness intervention in terms of time, group, and the interaction between time and groups ($p = 0.03$, 0.004, and 0.009). (2) In terms of the mindfulness level, the difference between the mindfulness group and the control group was not significant in the pre-test. The sprinters' mindfulness level was significant in the interaction between groups and that between groups and time after mindfulness intervention ($p = 0.027$ and 0.028).

Conclusion: Mindfulness training alleviated sprinters' competition anxiety by reducing sprinters' somatic state anxiety (SSA) and cognitive state anxiety (CSA), as well as improving state self-efficacy. The results provide guidance and references for Chinese sprinters' psychological problems.

KEYWORDS

sprinters competition state anxiety, mindfulness-acceptance-insight-commitment (MAIC) training, cognitive state anxiety (CSA), state of self-confidence (SSC), somatic state anxiety (SSA)

1 Introduction

Competition anxiety has been considered to be one of the most studied fields in sports psychology (Ong and Chua, 2021; Daley et al., 2024; Boughattas et al., 2022). It is defined as a response to the characteristics and/or similar states of stressful exercise-related situations. Individuals believe that this response is potentially stressful, which leads to a series of cognitive assessments, behavioral responses, and/or physiological arousal (Ford et al., 2017).

Past meta-analysis has proven the influence of competitive status anxiety on sports performance (Woodman and Hardy, 2003). CSA has a significantly negative impact on sports performance. In addition, high anxiety scenarios cause athletes to perform excessive error monitoring (Masaki et al., 2017) and reduce anticipation timing performance (Duncan et al., 2016). Competition anxiety increases the risk of sports injury for sprinters (Ford et al., 2017). Competitive status anxiety is a risk factor for skeletal muscle injury in sprinters (Cagle et al., 2017).

Chinese sprinters have demonstrated remarkable progress in their performance through scientific training methods in recent years, which resulted in a substantial and comprehensive advancement during the Tokyo Olympic cycle and a historic breakthrough (Xue Feng, 2022). Su Bingtian, clocking in at 9.83 s, established a new Asian record and secured his place in the men's 100-m semifinals at the Tokyo Olympics, which makes him the first Chinese athlete to advance to the final of this event (Wang, 2023). Ge Manqi and Xie Zhenye advanced to the women's 100 m and men's 200 m semifinals at 11.20 and 20.34 s, respectively. Simultaneously, Su Bingtian, along with Tang Xingqiang, Xie Zhenye, and Wu Zhiqiang, secured the bronze medal in the men's 100-m relay event, which achieved the highest level of participation by the Chinese Olympic delegation. Wu Yanni and Lin Yuwei, both accomplished athletes in women's 100-m hurdles, qualified for the 2024 Paris Olympics (Hongren and YaPing, 2022).

An increasing number of exceptional sprinters with remarkable achievements and distinctive characteristics are being discovered in the era of new media, which attracts attention and admiration from online users. Consequently, they have emerged as prominent Internet celebrity athletes. However, athletes' popularity on the Internet can overly increase athletes' exposure, which counters athletes' confident and optimistic sports mentality (Yue Hui and Xiangyang, 2023). The web celebrity status of sports stars means that they are under the panoramic surveillance of the network society and the expectations of the public and coaches (Kim et al., 2019). Web celebrity athletes with poorer mental health need to be acknowledged by public opinion, as they often experience psychological pressure stemming from the desire to win and the fear of losing (Xiao Li et al., 2022). Reardon et al. (2024) shows that excessive psychological stress in athletes can cause cognitive and somatic anxiety, negatively affecting the quality of their training and competition.

Improving sports performance has always been a basic goal for athletes to excel in their respective sports. Regardless of the time and effort spent, athletes continuously try to improve their skills and athletic level. According to Behroz's research, many athletes in professional teams are committed to training throughout the year and improving their sports performance to obtain bonuses or reach a professional level. Therefore, they win the high hopes of parents and coaches (Khodayari et al., 2011). Unfortunately, high hopes increase the pressure on athletes, which usually causes athletes' competition anxiety. When anxiety is not guided, athletes lose control, which decreases athletic performance (Cox et al., 2003).

Regarding the athlete cultivation system in China, the predominant focus on training and competitions results in an environment where many athletes are primarily centered around sports activities. Consequently, this emphasis restricts the development of a well-rounded social personality and a scientific perspective on life (Dennis et al., 2024). When the technical level reaches a certain height, athletes have ambiguous developmental goals, poor comprehension of high-level events, and poor adaptability due to the shortcomings of early emotional intelligence and personality shaping. The plateau phenomenon (Miller et al., 2024) of athletic ability further restricts the development of their athletic ability to a higher level. Targeted interventions should be implemented in their psychological wellbeing to facilitate the advanced development of athletes.

Concerning types of sports, individual sport athletes have higher cognitive anxiety scores and lower self-efficacy scores than group sport athletes (Pluhar et al., 2019). Individuals participating in individual sports who rely on distance mobilizers exhibit a higher susceptibility to competition anxiety than athletes engaged in team sports (Hossein et al., 2016).

A range of psychological interventions have been used in previous studies to assist athletes in managing competition-related anxiety. A variety of psychological interventions have been adopted to help athletes cope with anxiety in the competitive state. Psychological health problems are reduced (Schinke et al., 2021) to ensure that they do not affect athletes' training and competitions. Previous research has focused on utilizing various psychological techniques to aid athletes in coping with competition-induced anxiety [e.g., mental training (Fekih et al., 2021), self-talk training (Walter et al., 2019), and progressive relaxation training (Hussein et al., 2019)]. They are called psychological skill training (PST). Additional psychological interventions such as mindfulness training (Mehrsafar et al., 2019) and biofeedback training (Pusenjak et al., 2015) have gained increasing attention. Mindfulness intervention and PST are commonly used by most sports teams to deal with competition anxiety. Compared to mindfulness training, control-based PST emphasizes control to obtain optimal internal experience. However, the effect is passable. In contrast, mindfulness training that does not emphasize control and optimal internal experience allows athletes to focus more freely on current tasks (Gardner and Moore, 2004; Moore, 2009). Therefore, mindfulness training is used to intervene in the competition state anxiety of sprinters in this study.

Mindfulness has been described as "awareness that emerges through paying attention on purpose, in the present moment, and non-judgmentally to the unfolding of experience moment by moment" (Kabat-Zinn, 2019). Mental training based on mindfulness and acceptance has generated a great deal of interest and concern among researchers and practitioners in sports psychology, particularly within the context of the third wave of cognitive therapy (Bühlmayer et al., 2017). Mindfulness in this psychological training is derived from the Eastern Buddhism of Nei Kuan and Zen, as well as Western psychology. When combined with contemporary Western culture, it pioneers the integration of ancient Eastern wisdom into clinical psychotherapy and counseling, leading to the development of a range of mindfulness and acceptance-based mental training methods (Gang Yan et al., 2014).

Mindfulness was first applied by Kabat-Zinn in the context of athletes' daily training and Olympic preparation in sports (Demarzo, 2014). Mindfulness training and acceptance have attracted attention in sports due to their application and development in clinical and counseling psychology, addressing limitations in traditional psychological training. Research in sports suggests that this particular type of attention may be beneficial (Bühlmayer et al., 2017). Fortunately, mindfulness training methods have been developed specifically for athletes. The mainstream training methods with more systematic theories and wider application include mindfulness-acceptance-commitment (MAC) (Gardner and Moore, 2017), mindfulness sports performance enhancement (MSPE) (Hut et al., 2021), mindfulness-acceptance-based-interventions (MABIs) (Minkler et al., 2024), and mindfulness-acceptance-insight-commitment (MAIC) (Su et al., 2019).

In contrast to traditional psychological skills, the mindfulness training approach focuses on mind–body experiences (e.g., thoughts, physical sensations, and emotions) (Mohebi et al., 2021) rather than controlling or altering these experiences (Röthlin et al., 2020). The mainstream approaches to mindfulness training in sports have been widely utilized. They enhance athletic performance (Chang et al., 2023) by improving concentration (Gao and Zhang, 2023), flow state (Augustus et al., 2023), and confidence (Oguntuase and Sun, 2022) as well as reducing burnout (Zhang et al., 2023) and exercise anxiety (Blanck et al., 2018).

Positive mindfulness is negatively correlated with cognitive and somatic anxiety in cross-sectional designs, suggesting that positive mindfulness may reduce competition anxiety. Improved mindfulness positively affects performance-related factors such as emotional processing and attention control (Röthlin et al., 2020). MAIC can enhance athletes' attentional control, emotional processing, and resilience to failure (Röthlin et al., 2020), contributing to their overall psychological wellbeing (Evers et al., 2021).

The psychological problems of sprinters have become a common concern in sports training theory and practice with the rapid growth of the international competitiveness of China's sprint program. The study examined the effects of 7 weeks of systematic mindfulness training on the competition anxiety of sprinters, providing guidance and implications for Chinese sprinters.

2 Methods

2.1 Participants

The study recruited 24 athletes from sprinters ($M_{age} = 22.46 \pm 1.351$; 14 males and 10 females; 11 people with training years of less than 6 years and 13 people with training years of more than 6 years) through the Jilin Province Sports Association. G * Power (Faul et al., 2009) (power = 0.90, $\alpha = 0.05$, and effect size $f = 0.37$) was used for a previous efficacy analysis to estimate the minimum sample size. According to the calculation results, at least 18 sample sizes were required to test the variance-analysis interaction terms of 3 (time) × 2 (condition) repeated measurement. The Competitive State Anxiety Inventory-2 (CSAI-2) was issued to sprinters who met the standards through the Jilin Province Sports Association, and 232 sprinters were assessed for competitive status anxiety. Sorted using the anxiety scores, sprinters who met the criteria were invited to participate in the study. The inclusion criteria were as follows: participants had to be at least 18 years old; have no prior experience with mindfulness studies or participation in similar experimental studies or psychological interventions; and possess a mean competition anxiety score of 3.5 (derived from the average score of 232 sprinters, with competition state anxiety was calculated, and the average score of 25% of sprinters with higher competition state anxiety was 3.5). Additionally, participants must not have a history of psychiatric disorders; they should be capable of engaging in regular training sessions and competitions; they should be eligible to compete in the 100-m dash in the 21st National Collegiate Athletics Championships. Eligible athletes were randomly assigned to the mindfulness group and control group based on a computer-generated list of random times. Initially, 25 participants completed the pre-intervention survey with one excluded from the study. There were 24 final valid subjects, with 12 in the mindfulness group and 12 in the control group (Table 1). All athletes ultimately included in the analysis participated in all mindfulness sessions.

2.2 Procedure

Randomization was used to assign subjects to the mindfulness (intervention) group ($n = 12$) and the control group ($n = 12$). Athletes received interventions in the conference room of the university gymnasium every Saturday morning over 7 weeks, with each session lasting 60 min and occurring once weekly. The mindfulness group participated in a 7-week mindfulness intervention based on the mindfulness training content, while the control group did not receive guided exercises for mindfulness intervention. They were instructed to sit comfortably, relax, and allow their thoughts to wander freely, such as recalling daily life or imagining the future. A single-blind design (Kimberly MacLin, 2023) was adopted to control unrelated variables. The purpose and process arrangements of the test were kept confidential from the athletes. All participants were assessed in the pre-intervention stage (T0), the mid-intervention stage (T3), and the post-intervention stage (T7) (Hao, 2021). The Five Factors of Mindfulness and Competitive State Anxiety Scales were distributed to participants. The mindfulness intervention was facilitated by a sports psychologist who held a certification in mindfulness-based practices. All subjects signed the consent forms and had the right to withdraw at any time during the experiment. They were informed that they would receive a reward based on the completion of the tests.

TABLE 1 Participants demographics.

Characteristics	MAIC (n = 12)	Control (n = 12)	P
Age (M ± SD)	22.58 ± 1.311	22.33 ± 1.435	
Gender (%)			1.000
Females	41.7%	41.7%	
Males	58.3%	58.3%	
Training age (%)			0.698
5 years or less	41.7%	58.3%	
6 years and above	50.0%	50.0%	

MAIC: mindfulness training group. Control: control group. M: Mean. SD: standard deviation.

2.3 Study design

A 2 * 3 mixed experimental design was used. The effects of mindfulness training on mindfulness levels and competition anxiety in sprinters were examined. The group (mindfulness/control) was the between-subjects variable. Test time (T0 pre-test/T3 mid-test/T7 post-test) was the within-subjects variable. The dependent variables corresponded to the levels of mindfulness and competition anxiety. Athletes participated in the intervention in the conference room of the university gymnasium every Saturday morning. Each athlete was asked to perform 15 min of breathing exercises at home every day for 7 weeks after training. The insights gained from their pre-session practice before each mindfulness session were analyzed.

2.4 Mindfulness intervention

The intervention consisted of a 7-week MAIC program. The content was based on the *Mindfulness Training Manual for Athletes* by Si et al. and developed from the interviews of professional coaches in track and field. Mindfulness interventions were conducted by a master of sports psychology who was certified in mindfulness intervention. Specifics included the following aspects: (1) Preparation for mindfulness training included introducing the theory, facts, and basic methods of mindfulness training and helping athletes form a preliminary impression of the activity and arouse interest in participating. (2) Mindfulness included experiencing mindfulness through practice and guiding athletes to understand mindfulness in practice. (3) De-centering included helping athletes gradually shift from preoccupation to task attention through practice. (4) Acceptance included the mindfulness raisin exercise and mindfulness drinking practice, as well as experiencing and accepting all inner emotions and thoughts. (5) Values and awareness included helping athletes clarify the current direction of behaviors. (6) Commitment included transforming values into specific behaviors, helping athletes realize values, overcoming obstacles in the realization process, applying mindfulness, decentration, and receptive skills, and adhering to effective behaviors for values. (7) Integration included reviewing and synthesizing the skills learned in the first 6 classes so that athletes could overall understand mindfulness training. Table 2 shows the specific contents.

TABLE 2 Mindfulness-acceptance-insight-commitment (MAIC) training content.

Training topics	Training content and objectives
Mindfulness preparation	Introduce the theory, facts, and basic methods of mindfulness training; help athletes form a preliminary impression of the activity and arouse interest in participating.
Mindfulness	Body scanning exercises; assist athletes to fully understand their status, maintain objectivity, do not judge and react, and focus on the current situation.
Egocentrism reduction	Explain the concept of self-centeredness: guide athletes to gradually shift from self-preoccupation to task attention; perform mindfulness imagery exercise and mindful eating of grapes.
Acceptance	Mindfulness raisin exercise and mindfulness drinking practice; do not judge, do not react to inner experiences, and accept their existence as they are. Do not evaluate objective things with personal subjective intentions; instead, recognize and accept them as they are.
Value and consciousness	Mindfulness breathing and consciousness; focus on values and awareness; guide athletes to discover the meaning of their current behavior and the direction and motivation of thinking behavior, as well as to take responsibility for their behavior.
Commitment	The extension of values and consciousness: Values serve as the guiding compass and motivational impetus for athletes' behavior, while concentration affords them the means to allocate their time effectively. As athletes refine their state of consciousness, they become more adept at resolutely committing to and engaging in behaviors that resonate with their fundamental values.
Comprehensive review and consolidation	A comprehensive review and synthesis of the training provided in mindfulness intervention is provided, along with an integrated direction and guide for mindfulness practice and application after the mindfulness training course.

2.5 Measures

2.5.1 FFMQ

The FFMQ (Baer et al., 2006), translated and revised by Deng et al. (2011), includes 39 items. Five aspects are used to assess mindfulness: observing, describing, acting with awareness, non-judging of inner experience, and non-reacting to inner experience. The FFMQ has acceptable psychometric properties. Its subscales measure individual characteristics or traits (Kabat-Zinn, 2003). The scale utilizes a 6-point Likert scale format from 1 (not at all) to 6 (exactly). Higher scores reflect higher levels of mindfulness.

The FFMQ was used to calculate the subscale scores. The items were reverse-coded. The subscale scores were calculated by summing item scores. SPSS.27 was used for the reliability analysis of the FFMQ. The internal consistency of the current sample was 0.825 (Cronbach's α at baseline). Bartlett's test of sphericity, based on chi-square, showed a result of 1,945.061, with 136 degrees of freedom ($p < 0.001$). Cronbach's α for the subscales demonstrated good reliability: observing (0.783), describing (0.623), acting with awareness (0.873), non-judging of inner experience (0.799), and non-reacting to inner experience (0.642).

2.5.2 CSAI-2

The CSAI-2 (Cox et al., 2003) includes 27 items and 3 subscales: cognitive, somatic, and self-confidence anxiety. The inventory uses a 6-point Likert scale from 1 (not at all) to 6 (completely). Higher total scores are associated with higher levels of anxiety. There are 14 reverse-coded questions. The subscale scores were calculated by adding up the item scores. SPSS.27 was used for the reliability analysis of the CSAI-2. The internal consistency of the current sample was 0.899 (Cronbach's α at baseline). Bartlett's test of sphericity, based on chi-square, showed a result of 1,945.061, with 136 degrees of freedom ($p < 0.001$). Cronbach's α for the scale and its subscales ranged from 0.694 to 0.900, indicating high reliability.

2.6 Data analyses

The normality test (Shapiro–Wilk test) was performed before the statistical analysis. The independent t-test for normally distributed variables was used to compare the baseline variables of the two groups. General linear models were used to examine the impact of a 7-week mindfulness training program on competitive state anxiety by analyzing pre-intervention, mid-intervention, and post-intervention data. The between-group effects of the mindfulness training and control groups were further tested when the difference between the two groups was statistically significant. ANOVA and Bonferroni correction were used for multiple comparisons. η^2_p of the interaction effects of time and group was reported for two-by-two comparisons. The cutoff value of η^2_p was as follows: $\eta^2_p < 0.019$ represented a minute effect size; $0.02 < \eta^2_p < 0.059$ represented a small effect size; $0.06 < \eta^2_p < 0.139$ represented a medium effect size; $\eta^2_p > 0.14$ represented a large effect size (Cohen, 1988). All data were analyzed using SPSS 27.0. A p-value of ≤0.05 indicated statistical significance.

3 Results

3.1 FFMQ and CSAI-2 before mindfulness intervention

There were no statistically significant differences between the distribution of the mindfulness group and the control group in terms of gender and years of training (Table 1). There were no statistically significant differences between the two groups in terms of somatic, cognitive, and self-confidence anxiety, as well as in the dimensions of observing, describing, acting with awareness, non-judging of inner experience, and non-reacting to inner experience (Table 3).

3.2 CSAI-2 after mindfulness intervention

Table 4 indicates a decrease in the somatic anxiety of the mindfulness group mid- and post-intervention. Repeated measure ANOVA shows significant main effects for groups ($F = 16.23$, $p < 0.001$, and $\eta^2_p = 0.43$), time ($F = 5.05$, $p < 0.019$, and $\eta^2_p = 0.19$), and interaction ($F = 7.60$, $p < 0.004$, and $\eta^2_p = 0.257$). The simple effects of groups are not significant at pre-intervention ($F = 0.002$, $p = 0.965$, and $\eta^2_p = 0.000$) but significant at mid-intervention ($F = 6.29$, $p = 0.019$, and $\eta^2_p = 0.225$) and post-intervention ($F = 60.90$, $p = 0.001$, and $\eta^2_p = 0.735$).

Multiple comparisons reveal that somatic anxiety levels decreased progressively from mid-test to post-test within the mindfulness group. All results indicate significance ($p < 0.05$). Somatic anxiety is reduced sequentially from the mid- and post-tests in the control group, indicating no significance ($p > 0.05$). Somatic anxiety decreases at pre-, mid-, and post-intervention, reaching significant levels. There is a significant difference between pre- and mid-tests ($p < 0.024$), mid- and post-tests ($p < 0.004$), and pre- and post-tests ($p < 0.001$) in the mindfulness group. No difference exists among the pre-, mid-, and post-tests in the control group.

Table 4 displays increased and unchanged SSC in the mindfulness group and control group during and after the intervention. Repeated measure ANOVA results indicate that groups have significant main effects ($F = 8.49$, $p = 0.008$, and $\eta^2_p = 0.28$); however, those of time ($F = 0.49$, $p = 0.62$, and $\eta^2_p = 0.02$) and interaction effects between time and groups ($F = 2.60$, $p = 0.09$, and $\eta^2_p = 0.11$) are not significant. The test of groups' simple effects shows that they are not significant at pre-intervention ($F = 1.22$, $p = 0.28$, and $\eta^2_p = 0.05$.) but significant at mid-intervention ($F = 4.70$, $p = 0.04$, and η^2_p *= 0.18*) and post-intervention ($F = 11.97$, $p = 0.002$, and $\eta^2_p = 0.35$). The analysis of the simple effects of time reveals no significant differences in the mindfulness group ($F = 0.38$, $p = 0.69$, and $\eta^2_p = 0.04$) and control group ($F = 1.93$, $p = 0.17$, and $\eta^2_p = 0.16$).

The table demonstrates the decreased and unchanged CSA of the mindfulness group and the control group during and after the intervention. Repeated measures ANOVA indicates main effects are significant in groups ($F = 15.70$, $p = 0.001$, and $\eta^2_p = 0.42$) and time ($F = 4.19$, $p = 0.02$, and $\eta^2_p = 0.16$). However, they are not significant in the interaction between groups and time ($F = 5.24$, $p = 0.01$, and $\eta^2_p = 0.19$). The simple effects of groups shows that they are not significant at the pre-intervention ($F = 1.49$, $p = 0.24$, and $\eta^2_p = 0.06$) and mid-intervention ($F = 4.23$, $p = 0.05$, and $\eta^2_p = 0.16$) but significant at the post-intervention ($F = 48.88$, $p = 0.001$, and $\eta^2_p = 0.69$). The simple effects of time shows that they are significant in the mindfulness group ($F = 8.37$, $p = 0.002$, and $\eta^2_p = 0.45$) but not significant in the control group ($F = 0.08$, $p = 0.92$, and $\eta^2_p = 0.01$). Multiple comparisons indicate pre-, mid-, and post-tests sequentially decrease CSA due to mindfulness intervention. There are significant differences in CSA between pre- and post-tests ($p = 0.001$) as well as mid- and post-tests CSA ($p = 0.017$) in the mindfulness group. However, no significant difference exists in the CSA of pre-, mid-, and post-tests in the control group.

There is decreased and unchanged CSAI-2 in the mindfulness group and control group during and after the intervention. Repeated measures ANOVA results show significant main effects exist in groups ($F = 5.22$, $p = 0.03$, and $\eta^2_p = 0.99$) and time ($F = 6.43$, $p = 0.004$, and $\eta^2_p = 0.23$). However, they are not significant in the interaction between time and groups ($F = 5.20$, $p = 0.009$, and $\eta^2_p = 0.19$). The simple effects of groups show that they are not significant in the pre- and mid-tests but significant in the post-test ($F = 19.08$, $p = 0.001$, and $\eta^2_p = 0.46$). The simple effects of time show they are significant time due to the mindfulness intervention ($F = 8.92$, $p = 0.002$, and $\eta^2_p = 0.46$), but not significant under control conditions ($F = 0.03$, $p = 0.97$, and $\eta^2_p = 0.00$). Multiple comparisons reveal

TABLE 3 Descriptive statistics for study variables including t-test comparisons between groups.

	MAIC	Control	*T*	*P*
	M ± SD	M ± SD		
CSA	27.00 ± 7.97	30.58 ± 6.35	−1.219	0.236
SSA	27.00 ± 10.20	26.83 ± 7.74	0.045	0.685
SSC	38.92 ± 8.66	35.33 ± 7.16	1.104	0.281
CSAI-2	92.92 ± 14.74	90.67 ± 14.03	0.383	0.469
Observe	29.83 ± 6.46	28.58 ± 7.21	0.447	0.659
Describe	28.08 ± 6.69	26.08 ± 4.38	0.433	0.669
Non-judge	26.58 ± 4.32	26.58 ± 4.32	0.441	0.663
Non-react	25.25 ± 3.06	25.25 ± 3.05	−0.891	0.383
Act	23.75 ± 4.69	23.75 ± 4.69	−0.230	0.820
FFMQ	131.50 ± 22.215	130.25 ± 12.38	0.170	0.488

SSA: somatic state anxiety. CSA: cognitive state anxiety. SSC: state of self-confidence.

TABLE 4 Means, standard deviations, and two-way ANOVA statistics for outcome measures.

	MAIC	Control	Effect	ANOVA		
Measures	M ± SD	M ± SD		*F*	*P*	η^2_p
SSA						
Pre-intervention	27.00 ± 10.18	26.83 ± 7.74	A	16.23	0.001	0.43
Intervening	19.33 ± 3.49	25.83 ± 8.18	T	5.05	0.019	0.19
Post-intervention	19.25 ± 5.81	24.91 ± 6.41	A × T	7.60	0.004	0.26
Csa						
Pre-intervention	27.00 ± 7.96	30.58 ± 6.34	A	15.70	0.001	0.42
Intervening	22.00 ± 10.46	30.16 ± 8.92	T	4.19	0.02	0.16
Post-intervention	15.41 ± 8.59	21.58 ± 7.69	A × T	5.24	0.01	0.19
SSC						
Pre-intervention	38.91 ± 8.65	35.33 ± 7.16	A	8.49	0.008	0.28
Intervening	39.25 ± 7.77	33.50 ± 4.90	T	0.49	0.62	0.02
Post-intervention	42.16 ± 8.89	34.33 ± 5.14	A × T	2.60	0.09	0.11
Csai-2						
Pre-intervention	92.91 ± 14.73	90.66 ± 14.02	A	5.22	0.03	0.99
Intervening	80.58 ± 11.57	89.50 ± 16.01	T	6.43	0.004	0.23
Post-intervention	70.41 ± 5.55	89.50 ± 14.08	A × T	5.20	0.009	0.19

M represents the average; SD represents the difference in samples; A represents the effect size of the group; T represents the effect size of time; A × T represents the interaction between the group and time; F represents the variance analysis; P represents significance; η^2_p represents the effect size.

that the CSAI-2 values of pre-, mid-, and post-tests are sequentially lower due to the mindfulness training. The CSAI-2 values have significant differences between pre- and mid-tests ($p = 0.014$), mid- and post-tests ($p = 0.023$), and pre- and post-tests ($p = 0.001$) in the mindfulness group. However, no significant differences exist in the control group.

3.3 FFMQ after mindfulness intervention

Table 5 shows mean scores on all aspects of mindfulness increase over time, but there are slight differences in scores across aspects. This trend is supported by the within-subjects variance. The observing dimension is statistically significant considering the main effects of time ($F = 3.37$, $p = 0.04$, and $\eta^2 = 0.13$) and groups ($F = 14.33$, $p = 0.001$, and $\eta^2_p = 0.39$). The non-reacting to inner experience dimension is significant considering the main effect of the group ($F = 4.26$, $p = 0.05$, and $\eta^2_p = 0.16$) and interaction effects of group and time ($F = 6.60$, $p = 0.003$, and $\eta^2_p = 0.23$). Multiple comparisons show that scores on observing, describing, and non-reacting to inner experience dimensions are statistically significant during and after intervention ($p < 0.05$).

The FFMQ scores are improved significantly with mindfulness intervention. Repeated measures ANOVA shows significant main effects in groups ($F = 5.58$, $p = 0.027$, and $\eta^2_p = 0.20$) and the interaction between time and groups ($F = 3.87$, $p = 0.028$, and $\eta^2_p = 0.15$). However, they are not significant in time ($F = 1.60$, $p = 0.21$, and $\eta^2_p = 0.06$). The simple effects of groups show they are not significant before intervention ($F = 0.02$, $p = 0.87$, and $\eta^2_p = 0.001$) and during intervention ($F = 1.50$, $p = 0.23$, and $\eta^2_p = 0.06$), but significant after intervention ($F = 13.37$, $p = 0.001$, and $\eta^2_p = 0.38$). The simple effects of time show that they are significant in the mindfulness group ($F = 5.62$, $p = 0.011$, and $\eta^2_p = 0.35$), but not significant in the control group ($F = 0.32$, $p = 0.73$, and $\eta^2_p = 0.02$). Multiple comparisons indicate that the FFMQ values of pre-, mid-, and post-tests increase sequentially in the mindfulness group. The describing dimension values are significantly different between the pre- and post-tests ($p = 0.003$) as well as the mid- and post-tests ($p = 0.040$). No significant differences exist between observed dimensions ($p = 0.336$) in pre- and mid-tests. The dimensions are not significantly different in the control group in pre-, mid-, and post-tests.

4 Discussion

The effects of 7-week MAIC on the competitive state anxiety of sprinters were examined. Seven-week MAIC improved mindfulness and SSC and reduced SSA and CSA.

Mindfulness training was designed to help sprinters develop mindfulness skills and improve athletic performance. Athletes' level of mindfulness was measured using the FFMQ before, during, and after the intervention. The FFMQ could capture changes in mindfulness across experimental phases. The observed dimensions increased at all three-time points and were statistically significant. The non-reacting to the inner experience dimension was significant considering the interaction effects of time and group. Scores on observing, describing, and non-reacting to inner experience dimensions increased at all three-time points. However, the increases were statistically significant before and after the intervention. These results were consistent with published literature, suggesting that observing and non-reacting to inner experience dimensions were stronger inverse predictors of emotional symptoms, including fear and anxiety (Medvedev et al., 2018).

Competitive state anxiety was significantly reduced due to MAIC intervention, suggesting that mindfulness intervention was a key to clinical improvement. Fairly strong evidence suggested that mindfulness programs [e.g., mindfulness-based stress reduction therapy (Kabat-Zinn, 2013)] reduced the competitive anxiety level in

TABLE 5 Means, standard deviations, and two-way ANOVA statistics for outcome measures.

Measures	MAIC M ± SD	Control M ± SD	Effect	ANOVA F	ANOVA P	ANOVA η^2_p
Observe						
Pre-intervention	29.833 ± 6.464	28.583 ± 7.216	A	14.33	0.001	0.39
Intervening	32.500 ± 3.233	26.750 ± 5.276	T	3.37	0.04	0.13
Post-intervention	37.416 ± 5.45	28.500 ± 5.402	A × T	2.96	0.06	0.12
Describe						
Pre-intervention	27.083 ± 6.694	26.083 ± 4.378	A	3.90	0.06	0.15
Intervening	28.000 ± 4.327	26.166 ± 4.427	T	1.81	0.17	0.08
Post-intervention	31.500 ± 5.616	26.500 ± 3.919	A × T	1.24	0.30	0.05
Non-judge						
Pre-intervention	27.583 ± 6.556	26.583 ± 4.316	A	0.92	0.35	0.04
Intervening	28.583 ± 3.117	28.416 ± 4.851	T	1.21	0.31	0.05
Post-intervention	30.250 ± 4.287	27.250 ± 5.154	A × T	0.79	0.46	0.03
Non-react						
Pre-intervention	23.666 ± 5.348	25.250 ± 3.048	A	4.26	0.05	0.16
Intervening	26.083 ± 6.200	23.416 ± 3.824	T	2.14	0.13	0.09
Post-intervention	30.333 ± 5.898	23.166 ± 2.790	A × T	6.60	0.003	0.23
Act						
Pre-intervention	23.333 ± 4.163	23.750 ± 4.692	A	1.01	0.33	0.04
Intervening	22.500 ± 4.078	25.666 ± 6.169	T	2.67	0.08	0.11
Post-intervention	20.583 ± 5.664	21.083 ± 6.999	A × T	0.54	0.59	0.02
Ffmq						
Pre-intervention	127.416 ± 21.873	126.083 ± 13.500	A	5.58	0.027	0.20
Intervening	132.083 ± 12.915	133.833 ± 19.237	T	1.60	0.21	0.06
Post-intervention	144.833 ± 15.330	126.500 ± 15.733	A × T	3.87	0.028	0.15

M represents the average; SD represents the difference in samples; A represents the effect size of the group; T represents the effect size of time; A × T represents the interaction between the group and time; F represents the variance analysis; P represents significance; η^2_p represents the effect size.

athletes (Gan et al., 2024). However, flow states (Liu, 2023) have shown promising results for psychological health, suggesting the utility of the mindfulness intervention in the study.

Previous research has shown that mindfulness training can increase athletes' mindfulness levels and promote athletes' performance (Zhang et al., 2016). It is confirmed by comparing the results of the mindfulness and control groups. However, only the observed dimensions and the FFMQ have the main effect of time. The likely explanation is that athletes' engagement in mindfulness exercises is limited, and they have not fully integrated these practices into their routines.

Results from recent studies and meta-analyses suggest that the mindfulness intervention can alleviate athletes' anxiety levels (Deck et al., 2022). Additionally, it provides a strong evidence base for applying psychological intervention to reduce athletes' competitive state anxiety (Ong and Chua, 2021). Athletes in the mindfulness group decrease SSA and CSA and increase SSC. Importantly, this positive effect is immediately visible in the training, demonstrating the relative immediacy of the mindfulness training. These results are similar to those of imagery (Fekih et al., 2021) and self-talk training (Walter et al., 2019), which are commonly used in sports psychology training. The process integration hypothesis proposed by Wang suggests that athlete choking arises because of personality factors, performance expectations, and spectators (Jing et al., 2018). Mindfulness practice prompts athletes to cultivate an open and non-judgmental attitude toward their present thoughts and emotions. It reduces self-critical thinking, which can be distressing (Gardner and Moore, 2017). Consequently, mindfulness training can help improve athletes' psychological conditions during competition.

5 Conclusion

Mindfulness training has been systematically applied to sports as a psychological intervention. Mindfulness training was innovatively applied to measure the changes in the competition anxiety of sprinters under mindfulness intervention. Mindfulness intervention could significantly improve the mindfulness level of sprinters and reduce the anxiety of sprinters in competition. Mindfulness training after regular training sessions increased athletes' self-confidence and reduced physical state anxiety and cognitive state. Specifically, enhanced self-confidence improved the sports performance of athletes because the subjects in the study have achieved good results in national track and field competitions. The psychological problems of sprinters have become a common concern in the sports training theory and practice with the rapidly growing international competitiveness of China's sprint program. Athletes were recommended to arrange mindfulness training rationally according to their convenience to obtain the ideal psychological state and sports performance in daily training or competitions.

6 Limitations

Limitation 1: Small sample sizes may reduce the effectiveness of the study due to the limited number of sprinters who meet our inclusion and exclusion criteria. Limitation 2: The control group could not receive conventional psychological counseling due to the researchers' limited professionalism and manpower. Therefore, the results of the study should be interpreted cautiously.

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 Northeastern Electric Power 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

MY: Writing – original draft, Writing – review & editing. GD: Writing – review & editing. CG: Methodology, Resources, Writing – original draft, Writing – review & editing.

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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.2024.1418094/full#supplementary-material

References

Augustus, A., Zizzi, S., Voelker, D., and Costalupes, B. (2023). Living your best life: the mindful pursuit of student-athlete thriving. *Asian J. Sport Exerc. Psychol.* 4, 11–20. doi: 10.1016/j.ajsep.2023.09.004

Baer, R. A., Smith, G. T., Hopkins, J., Krietemeyer, J., and Toney, L. (2006). Using self-report assessment methods to explore facets of mindfulness. *Assessment* 13, 27–45. doi: 10.1177/1073191105283504

Blanck, P., Perleth, S., Heidenreich, T., Kröger, P., Ditzen, B., Bents, H., et al. (2018). Effects of mindfulness exercises as stand-alone intervention on symptoms of anxiety and depression: systematic review and meta-analysis. *Behav. Res. Ther.* 102, 25–35. doi: 10.1016/j.brat.2017.12.002

Boughattas, W., Ben Salha, M., and Moella, N. (2022). Mental training for young athlete: a case of study of NLP practice. *SSM Mental Health* 2:100076. doi: 10.1016/j.ssmmh.2022.100076

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

Cagle, J. A., Overcash, K. B., Rowe, D. P., and Needle, A. R. (2017). Trait anxiety as a risk factor for musculoskeletal injury in athletes: a Crit ically appraised topic. *Int. J. Athl. Ther. Train.* 22, 26–31. doi: 10.1123/ijatt.2016-0065

Chang, Y. K., Gill, D. L., Creswell, J. D., Chen, D. T., Lin, C. Y., Chu, C. H., et al. (2023). Effect of mindfulness-based intervention on endurance performance under pressure and performance-relevant mental attributes, an interdisciplinary perspective: protocol for a mindfulness-based peak performance (MBPP) trial. *Contemp. Clin. Trials* 129:107175. doi: 10.1016/j.cct.2023.107175

Cohen, J. (1988). Statistical power analysis for the behavioral sciences. New York: Lawrence Erlbaum Associates Publishers.

Cox, R. H., Martens, M. P., and Russell, W. D. (2003). Measuring anxiety in athletics: the revised competitive state anxiety inventory–2. *J. Sport Exerc. Psychol.* 25, 519–533. doi: 10.1123/jsep.25.4.519

Daley, M. M., Reardon, C. L., Claudia, L., and Reardon, M. D. (2024). Mental health in the youth athlete. *Clin. Sports Med.* 43, 107–126. doi: 10.1016/j.csm.2023.06.003

Deck, S., Kouali, D., and Hall, C. (2022). Effects of imagery and mindfulness on anxiety, confidence, mental well-being, and performance in shot putt throwers: a case study. *J. Emerg. Sport Stud.* doi: 10.26522/jess.v1i.3701

Demarzo, M. M. (2014). Mindfulness applied to high performance athletes: a case report. *Actas Esp. Psiquiatr.* 43, 1–90.

Deng, Y.-Q., Liu, X.-H., Rodriguez, M. A., and Xia, C.-Y. (2011). The five facet mindfulness questionnaire: psychometric properties of the Chinese version. *Mindfulness* 2, 123–128. doi: 10.1007/s12671-011-0050-9

Dennis, B., Andreas, S., Nygren, J., Ntoumanis, N., and Ivarsson, A. (2024). The effects of interpersonal development programmes with sport coaches and parents on youth athlete outcomes: a systematic review and meta-analysis. *Psychol. Sport Exerc.* 70:102558. doi: 10.1016/j.psychsport.2023.102558

Duncan, M. J., Smith, M., Bryant, E., Eyre, E., Cook, K., Hankey, J., et al. (2016). Effects of increasing and decreasing physiological arousal on anticipation timing performance during competition and practice. *Eur. J. Sport Sci.* 16, 27–35. doi: 10.1080/17461391.2014.979248

Evers, A. G., Somogie, J. A., Wong, I. L., Allen, J. D., and Cuevas, A. G. (2021). The adaptation and evaluation of a pilot mindfulness intervention promoting mental health in student athletes. *J. Clin. Sport Psychol.* 15, 206–226. doi: 10.1123/jcsp.2019-0083

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

Fekih, S., Zguira, M. S., Koubaa, A., Bettaieb, A., Hajji, J., Bragazzi, N. L., et al. (2021). Effects of mental training through imagery on the competitive anxiety of adolescent tennis players fasting during Ramadan: a randomized, controlled experimental study. *Front. Nutr.* 8:713296. doi: 10.3389/fnut.2021.713296

Ford, J., Ildefonso, K., Jones, M., and Arvinen-Barrow, M. (2017). Sport-related anxiety: current insights. *Open Access J. Sports Med.* 8, 205–212. doi: 10.2147/OAJSM.S125845

Gan, Y., Wang, R., Wang, X., Li, J., and Fan, H. (2024). Who benefits more from mindfulness? A preliminary study exploring moderating effect of personality traits on competition anxiety in athletes. *Int. J. Sports Sci. Coaching* 19, 390–400. doi: 10.1177/17479541231159171

Gang Yan, S., Ge Zi, Z., Ning, S., and Qing Chun, Z. (2014). The origin of ideas and content design of mindfulness training programs for Chinese athletes. *Chin. J. Sports Med.* 33, 58–63. doi: 10.16038/j.1000-6710.2014.01.012

Gao, Q., and Zhang, L. (2023). Brief mindfulness meditation intervention improves attentional control of athletes in virtual reality shooting competition: evidence from fNIRS and eye tracking. *Psychol. Sport Exerc.* 69:102477. doi: 10.1016/j.psychsport.2023.102477

Gardner, F. L., and Moore, Z. E. (2004). A mindfulness-acceptance-commitment-based approach to athletic performance enhancement: theoretical considerations. *Behav. Ther.* 35, 707–723. doi: 10.1016/S0005-7894(04)80016-9

Gardner, F. L., and Moore, Z. E. (2017). Mindfulness-based and acceptance-based interventions in sport and performance contexts. *Curr. Opin. Psychol.* 16, 180–184. doi: 10.1016/j.copsyc.2017.06.001

Hao, Y. (2021). Several multi-factor experimental design and statistical analysis methods are applied in sports research. *J. Beijing Sport Univ.* 33, 75–78. doi: 10.19582/j.cnki.11-3

Hongren, C., and YaPing, Z. (2022). Diagnosis of key techniques and optimization of training strategies of outstanding female 100 m hurdlers in China. *J. Henan Normal Univ.* 50, 148–156. doi: 10.16366/j.cnki.1000-2367.2022.05.021

Hossein, S., Zahra, H., and Seyed, R. A. H. (2016). Comparative analysis of competitive state anxiety among team sport and individual sport athletes in Iran. *Phys. Educ. Stud.* 20, 57–61. doi: 10.15561/20755279.2016.0508

Hussein, R., Siti Hajar, M., Savardelavar, M., and Kueh, Y. C. (2019). The effects of progressive muscular relaxation on novice archers' state anxiety, heart rete and performance scores. *Int. J. Public Health Clin. Sci.* 6, 96–112. doi: 10.32827/ijphcs.6.4.96

Hut, M., Glass, C. R., Degnan, K. A., and Minkler, T. O. (2021). The effects of mindfulness training on mindfulness, anxiety, emotion dysregulation, and performance satisfaction among female student-athletes: the moderating role of age. *Asian J. Sport Exerc. Psychol.* 1, 75–82. doi: 10.1016/j.ajsep.2021.06.002

Jing, W., Zhi, Q., and Jin Hua, L. (2018). Stress and the phenomenon of "choking": a systematic analysis based on process theory. *Sports Sci.* 38, 19–34. doi: 10.16469/j.css.201812003

Kabat-Zinn, J. (2003). Applying generalizability theory to differentiate between trait and state in the five facet mindfulness questionnaire (FFMQ). *Mindfulness* 10, 144–156. doi: 10.1007/s12671-020-013247

Kabat-Zinn, J. (2019). Foreword: seeds of a necessary global renaissance in the making: the refining of psychology's understanding of the nature of mind, self, and embodiment through the lens of mindfulness and its origins at a key inflection point for the species. *Curr. Opin. Psychol.* 28, xi–xvii. doi: 10.1016/j.copsyc.2019.02.005

Kabat-Zinn, J. (2013) The foundation of mindfulness practice: attitudes commitment. London: Routledge.

Khodayari, B., Saiiari, A., and Dehghani, Y. (2011). Comparison relation between mental skills with sport anxiety in Sprint and endurance runners. *Procedia. Soc. Behav. Sci.* 30, 2280–2284. doi: 10.1016/j.sbspro.2011.10.445

Kim, S., Oh, T., Lee, S., and Andrew, D. P. S. (2019). Relationships between met-expectation and attitudinal outcomes of coaches in intercollegiate athletics. *Sport Manag. Rev.* 22, 477–490. doi: 10.1016/j.smr.2018.06.007

Kimberly MacLin, M. (2023). Experimental Design in Psychology. New York: Routledge Publishers.

Liu, W. (2023). Retracted: intervention of fluency and anxiety in mindfulness training of shooting. *Scanning* 2022:1. doi: 10.1155/2022/6069561

Masaki, H., Maruo, Y., Meyer, A. H., and Jcak, G. (2017). Neural correlates of choking under pressure: athletes high in sports anxiety monitor errors more when performance is being evaluated. *Dev. Neuropsychol.* 42, 104–112. doi: 10.1080/87565641.2016.1274314

Medvedev, O. N., Norden, P. A., Krägeloh, C. U., and Siegert, R. J. (2018). Investigating unique contributions of dispositional mindfulness facets to depression, anxiety, and stress in general and student populations. *Mindfulness* 9, 1757–1767. doi: 10.1007/s12671-018-0917-0

Mehrsafar, A. H., Strahler, J., Gazerani, P., Khabiri, M., Sánchez, J. C. J., Moosakhani, A., et al. (2019). The effects of mindfulness training on competition-induced anxiety and salivary stress markers in elite Wushu athletes: a pilot study. *Phys. Behav.* 210:112655. doi: 10.1016/j.physbeh.2019.112655

Miller, T. W., Coates, J., Plateau, C. R., and Barker, J. B. (2024). Exploring the barriers and facilitators to mental health help-seeking behaviours in British elite track and field athletes. *J. Appl. Sport Psychol.* 36, 98–118. doi: 10.1080/10413200.2023.2197962

Minkler, T. O., Zizzi, S. J., and Jake Follmer, D. (2024). The roles of readiness and dosage in predicting outcomes of a mindful sport performance enhancement intervention with U.S. college student-athletes. *Psychol. Sport Exerc.* 70:102539. doi: 10.1016/j.psychsport.2023.102539

Mohebi, M., Sadeghi-Bahmani, D., Zarei, S., Gharayagh Zandi, H., and Brand, S. (2021). Examining the effects of mindfulness–acceptance–commitment training on self-compassion and grit among elite female athletes. *Int. J. Environ. Res. Public Health* 19:134. doi: 10.3390/ijerph19010134

Moore, Z. E. (2009). Theoretical and empirical developments of the mindfulness acceptance-commitment (MAC) approach to performance enhancement. *J. Clin. Sport Psychol.* 3, 291–302. doi: 10.1123/jcsp.3.4.291

Oguntuase, S. B., and Sun, Y. (2022). Effects of mindfulness training on resilience, self-confidence and emotion regulation of elite football players: the mediating role of locus of control. *Asian J. Sport Exerc. Psychol.* 2, 198–205. doi: 10.1016/j.ajsep.2022.08.003

Ong, N. C. H., and Chua, J. H. E. (2021). Effects of psychological interventions on competitive anxiety in sport: a meta-analysis. *Psychol. Sport Exerc.* 52:101836. doi: 10.1016/j.psychsport.2020.101836

Pluhar, M., Caitlin, M., Griffith, K. L., Christino, M. A., Sugimoto, D., and Meehan III, W. P. (2019). Team sport athletes may be less likely to suffer anxiety or depression than individual sport athletes. *J. Sports Sci. Med.* 3, 490–496. doi: 10.1080/07448481.2019.1707836

Pusenjak, N., Grad, A., Tusak, M., Leskovsek, M., and Schwarzlin, R. (2015). Can biofeedback training of psychophysiological responses enhance athletes' sport performance? A practitioner's perspective. *Phys. Sports Med.* 43, 287–299. doi: 10.1080/00913847.2015.1069169

Reardon, C. L., Gorczynski, P., Hainline, B., Hitchcock, M., and Rice, S. (2024). Anxiety Disorders in Athletes. *Clin. Sports Med.* 43, 33–52. doi: 10.1016/j.csm.2023.06.002

Röthlin, P., Horvath, S., Trösch, S., Holtforth, M. G., and Birrer, D. (2020). Differential and shared effects of psychological skills training and mindfulness training on performance-relevant psychological factors in sport: a randomized controlled trial. *BMC Psychol.* 8:80. doi: 10.1186/s40359-020-00449-7

Schinke, R. J., Giffin, C., Cosh, S., Douglas, K., Rhind, D., Harwood, C., et al. (2021). International society of sport psychology position stand: mental health through occupational health and safety in high performance sport. *Int. J. Sport Exerc. Psychol.* 123:20. doi: 10.1080/1612197X.2021.1992857

Su, N., Si, G., and Zhang, C.-Q. (2019). Mindfulness and acceptance-based training for Chinese athletes: the mindfulness-acceptance-insight-commitment (MAIC) program. *J. Sport Psychol. Action* 10, 255–263. doi: 10.1080/21520704.2018.1557772

Walter, N., Nikoleizig, L., and Alfermann, D. (2019). Effects of self-talk training on competitive anxiety, self-efficacy, volitional skills, and performance: an intervention study with junior sub-elite athletes. *Sports* 7:148. doi: 10.3390/sports7060148

Wang, H. (2023). Data analysis and statistics of Chinese men's 100m performance development prediction in recent 20 years based on SPSS software. In second international conference on statistics. *Appl. Math. Comput. Sci.* 12597, 474–479. doi: 10.1117/12.2672130

Woodman, T., and Hardy, L. (2003). The relative impact of cognitive anxiety and self-confidence upon sport performance: a meta-analysis. *J. Sports Sci.* 21, 443–457. doi: 10.1080/0264041031000101809

Xiao Li, Z., Cheng Liang, L., Bi Zhen, L., Ming Xin, Z., and Xin Lei, W. (2022). Reality review and path selection of the development of professional pports internet celebrity phenomenon in the attention economy era. *J. Shenyang Sports Inst.* 41, 138–144. doi: 10.12163/j.ssu.20212239

Xue Feng, Z. (2022). Progress and trends in scientific training for the 100 m sprint—reflections based on exercise biology and methodology. *Sports Sci.* 42, 3–11. doi: 10.16469/j.css.202202001

Yue Hui, Z., and Xiangyang, M. (2023). The derivative logic, risk scrutiny and avoidance strategies of the Netflixization phenomenon of sports stars. *J. Guangzhou Sports Inst.* 43, 120–128. doi: 10.13830/j.cnki.cn44-1129/g8.20

Zhang, C.-Q., Li, X., Si, G., Chung, P. K., Huang, Z., and Gucciardi, D. F. (2023). Examining the roles of experiential avoidance and cognitive fusion on the effects from mindfulness to athlete burnout: a longitudinal study. *Psychol. Sport Exerc.* 64:102341. doi: 10.1016/j.psychsport.2022.102341

Zhang, C.-Q., Si, G., Duan, Y., Lyu, Y., Keatley, D. A., and Chan, D. K. C. (2016). The effects of mindfulness training on beginners' skill acquisition in dart throwing: a randomized controlled trial. *Psychol. Sport Exerc.* 22, 279–285. doi: 10.1016/j.psychsport.2015.09.005

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The effect of reward and voluntary choice on the motor learning of serial reaction time task

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Objective: Reward and voluntary choice facilitate motor skill learning through motivation. However, it remains unclear how their combination influences motor skill learning. The purpose of the present study is to investigate the effects of reward and voluntary choice on motor skill learning in a serial reaction time task (SRTT).

Methods: Participants completed six parts of SRTT, including pre-test, training phase, immediate post-test, a random session, delayed post-test, and retention test on the following day. During the training phase, participants were divided into four groups (reward_choice, reward_no-choice, no-reward_choice, no-reward_no-choice). In the reward condition, participants received reward for correct and faster (than a baseline) responses while those in the no-reward groups did not. For the choice manipulation, participants in the voluntary choice groups chose the color of the target, whereas in the forced choice groups, the same color was assigned by the computer.

Results: The results showed that the four groups did not exhibit any significant differences in reaction time and error rate in the pre-test phase. Importantly, both reward and voluntary choice significantly enhanced sequence-specific learning effects, while no interaction was found. No significant effects of reward and voluntary choice were observed in the retention test.

Conclusions: These findings suggest that reward and voluntary choice enhance motor skill performance and training independently, potentially at the action-selection level, which implies different mechanisms underlying the influences of reward and voluntary choice.

KEYWORDS

motor learning, reward, voluntary choice, motivation, serial reaction time task

1 Introduction

Motor skill learning is crucial to human adaptation and development, as it is involved in a wide range of activities, including but not limited to typing, driving vehicles, and playing sports. Motor skill learning is characterized by a number of fundamental features, such as optimal movement selection and execution, improved movement speed and accuracy, as well as decreased movement variability and error (Yadav and Duque, 2023). Action selection and execution are two essential procedural components of motor skill learning (Diedrichsen and Kornysheva, 2015). Action selection involves the decision-making process where an individual chooses the most appropriate action from a set of possible actions (Kim et al., 2021). Execution, conversely, is the specification of actual muscle commands. Among the numerous paradigms of studying motor skill learning, the serial reaction time task (SRTT) specifically focuses on the action-selection level (Diedrichsen and Kornysheva, 2015; Rowland and Shanks, 2006). During SRTT, participants need to press the corresponding key according to the target location as quickly as possible. Reward and voluntary choice were often used to improve motor skill learning (for reviews, see Wulf and Lewthwaite, 2016; Zhao et al., 2024). However, little is known about the interaction or combining effect of reward and voluntary choice on motor skill performance and training.

External rewards, such as money and praise, are usually used in studies investigating the reward effect on a series of cognitive processes, such as attentional selection, conflict control and action et al. (Chelazzi et al., 2013; Kang et al., 2019, 2024; Grehl et al., 2022; Martinez et al., 2024; Sugawara et al., 2012; Vassiliadis et al., 2021). Previous studies have shown that participants who received rewards were more engaged in tasks and had better skill acquisition (Anderson et al., 2020; Palminteri et al., 2011; Vassiliadis et al., 2021; Wächter et al., 2009) and consolidation (Abe et al., 2011; Vassiliadis et al., 2021). For example, Wächter et al. (2009) investigated the differential impact of reward and punishment on motor learning. They trained participants on SRTT and found that the reward group showed more significant learning of sequence than the punished and control groups, as evidenced by greater reaction time (RT) savings when comparing the sequence block with random blocks. A recent study used the pinch-grip force task to examine the effect of reward on motor learning and revealed that compared to providing feedback alone, training with reward markedly enhanced skill performance and consolidation (Vassiliadis et al., 2021). These findings are consistent with reinforcement theory suggesting that rewarded behavior tends to be reinforced and repeated over time to increase the frequency of achieving rewarding outcomes in the future (Schultz, 2006). Nonetheless, Bacelar et al. (2020) investigated the influence of reward and punishment on action selection and action execution and did not find differences between the reward (or punishment) group and the neutral group. In the task of Bacelar et al. (2020), the reward or punishment depended on a skill-irrelevant choice (a visual category task), which may influence the effects of reward and punishment. In the task of Bacelar et al. (2020), participants performed a category-learning task (action selection) followed by a golf-putting task (action execution). The reward or punishment on action selection was dependent on a skill-irrelevant choice (i.e., choosing the correct target in the category-learning task), which may influence the effects of reward and punishment. It is worth noting that Bacelar et al. (2020) tried to examine the effects of reward and punishment on action selection and action execution that were different from the two levels of skill learning (action selection and action execution) proposed by Diedrichsen and Kornysheva (2015), in which action selection activated appropriate spatiotemporal pattern of muscle activity for following execution. The influence of reward effect on motor skill learning, especially action selection and action execution, needs further investigation.

Voluntary choice was often used to elicit autonomy, which is an important factor in motor skill performance and learning (Sanli et al., 2013). Previous studies have demonstrated that allowing participants to make their own choices regarding the practice variables, such as the use of assistive devices, practice schedule and the receipt of feedback could be helpful in improving their subsequent performance (Keetch and Lee, 2007; Post et al., 2011; Wulf et al., 2001). For example, when learning a basketball set shot, the self-control group could freely decide the amount of practice and the spacing between each shot, while the yoked group was matched with their counterparts in the self-control group in terms of practice schedule. The former showed a higher accuracy in the retention test (Post et al., 2014). Carter et al. (2014) revisited earlier findings on self-controlled feedback schedules, comparing different timing strategies for feedback requests in a task. They found that participants who made feedback decisions after a trial or both before and after a trial performed significantly better in retention and transfer tasks than those who made decisions before a trial or in the yoked groups. Furthermore, this facilitating effect was also observed when the choice was irrelevant to the task (Grand et al., 2017; Lewthwaite et al., 2015; Wulf et al., 2018). For example, Lewthwaite and colleagues conducted two experiments to investigate whether task-irrelevant choices could facilitate motor skill learning (Lewthwaite et al., 2015). In their study, one group could choose the color of golf balls before a golf-putting task (Experiment 1) or choose which painting to hang on the wall before a balance task (Experiment 2), while the control group was yoked to choices made by the choice group. The results showed that the choice group exhibited superior skill performance and retention in both tasks. One possible explanation is that making voluntary choices helps individuals gain control over the external environment, which satisfies their psychological need of autonomy (Deci and Ryan, 1987; Ryan and Deci, 2000). The OPTIMAL (Optimizing Performance through Intrinsic Motivation and Attention for Learning) theory, proposed by Wulf and Lewthwaite (2016), provides a framework to elucidate how autonomy influences motor skill learning. The theory suggests that autonomy can strengthen the goal-action coupling not only directly but through enhanced expectancies, which increase self-efficacy and intrinsic motivation, facilitating motor performance and learning.

Although there was evidence supporting the positive effect of voluntary choice on motor skill learning, the effect of voluntary choice was limited (McKay et al., 2023, 2022; Parma et al., 2024). McKay et al. (2022) included 73 articles on self-controlled learning and detected a small effect of self-controlled practice ($g = -0.11$ to 0.26) after controlling for selection bias, suggesting a negligible distinction between self-controlled and yoked practice conditions. Additionally, some empirical studies with large sample sizes have failed to observe the learning benefit of self-controlled practice (e.g., McKay and Ste-Marie, 2020a; St. Germain et al., 2023, 2022). For example, St. Germain et al. (2022) manipulated both choice availability and feedback characteristics in a handle-moving task. The results indicated that groups with the opportunity to choose when to receive feedback did not show any significant reduction in spatial and timing error compared to yoked groups. They concluded that contrary to voluntary choice, feedback was more critical for skill acquisition in a motor adaptation task, as it may have provided sufficient information for movement modulation relative to the task goal. However, it is important to note that choosing feedback schedule is different from choosing incidental things (such as the color of a ball). Feedback is directly related to performance-based adjustment and has a significant impact on an individual's expectancies. The present study mainly focused on the selection of task-irrelevant stimuli.

Furthermore, previous research investigating the impact of voluntary choice on motor skill learning has predominantly focused on the execution level, for example, golf-putting (An et al., 2020; McKay and Ste-Marie, 2020a), dart-throwing (Ikudome et al., 2019; McKay and Ste-Marie, 2020b), while its effects on the selection level remain underexplored. Recent studies have shown that voluntary choice can facilitate cognitive processing (Luo et al., 2022, 2024). Recent studies have shown that voluntary choice can facilitate performance on cognitive tasks. For instance, in a study by Luo et al. (2022), participants could either freely choose a picture (in the voluntary choice condition) or choose the selected picture (in the forced choice condition) as the task background before completing a visual search task. The results showed a reduced RT in subsequent task performance following a voluntary choice compared to a forced choice. The authors suggested that the belief of control from choice-outcome causation had a general facilitating effect on the process of response. Considering that action selection is essentially a cognitive process, whether and how voluntary choice influences the action-selection level of motor skill performance and training remain further studied.

The purpose of the present study was to examine the combined effect of reward and voluntary choice on motor skill learning in a serial reaction time task. The experiment was conducted on two consecutive days comprising six parts: pre-test, training, immediate post-test, a random session, delayed post-test, and retention test on day 2. The experimental procedure was adapted from previous studies (Doppler et al., 2019). During the training phase, we manipulated both reward and voluntary choice which combined to form four training conditions (i.e., reward_choice, reward_no-choice, no-reward_choice, no-reward_no-choice), and participants were assigned to these four groups accordingly. Specifically, participants in the reward groups received performance-dependent monetary rewards, while participants in the no-reward groups did not receive any rewards. Participants in the voluntary choice groups could choose the color of the target stimulus before starting each 12-trial training, while the color was predetermined for those in the no-choice groups, which matched their counterparts in the voluntary choice groups. Two important dependent variables index SRTT performance and learning were calculated, that is, general learning (GL) and sequence-specific learning (SSL) (Dovern et al., 2011; Meier and Cock, 2014). Specifically, GL effect indicates performance improvement due to repetitive practice in motor response, usually indexed by the RT difference between the pre-test and immediate post-test. SSL indicates performance improvement due to the acquisition of implicit, sequence-specific knowledge. In the current experimental procedure, since the random session and the immediate post-test achieve the same level of learning in motor response (i.e., general learning), the RT difference between the random session and the immediate post-test session may indicate SSL. However, the increased RT in the random session may be due to participants' fatigue, so a delayed post-test was added to control for the potential fatigue effects. Thus, SSL is calculated by the RT difference between the random session and the mean of two post-tests. In accordance with previous studies showing that reward expectation facilitates goal-directed task performance, we predicted that reward would improve SRTT performance in the training phase and post-tests as measured by GL and SSL. Previous studies on task-irrelevant choice demonstrated that while choice did not facilitate performance during practice, it did benefit skill retention or transfer (Iwatsuki and Otten, 2020; Lewthwaite et al., 2015; Wulf et al., 2014). Therefore, we expected that voluntary choice would facilitate skill retention. Moreover, the OPTIMAL illustrates that extrinsic reward and autonomy can reinforce the goal-action coupling, maintaining a focus on the task goal and reducing a self-focus, which leads to enhanced motor performance and learning (Wulf and Lewthwaite, 2016). We hypothesized that a combination of reward and voluntary choice would positively influence the performance and learning of the SRTT.

2 Methods

2.1 Participants

A power analysis was conducted using the option ANOVA: fixed effects, special, main effects and interactions in G*Power 3.1 with the following parameters: effect size $f = 0.27$, $\alpha = 0.05$, $\beta = 0.20$, numerator $df = 1$, and number of groups = 4. The analysis revealed a total sample size of 110. The chosen effect size was according to a meta-analysis of published self-controlled learning experiments, which reported a moderate benefit of self-controlled practice, $g = 0.54$ (McKay et al., 2022). Although the effect size was slightly higher than the overall estimate ($g = 0.44$) of McKay et al. (2022), it was still used to calculate the sample size because the empirical studies (e.g., Lewthwaite et al., 2015; Post et al., 2014; Wulf et al., 2018) cited in the present study showed a moderate to high effect sizes for choice ($g > 0.7$) and research funding was limited. The present study recruited 119 participants (23 males, $M_{age} = 20.05$, SD = 2.32) in total from universities in Beijing. Participants were randomly assigned into four groups, that is, a reward_ choice group (RC), a reward_no-choice group (RNC), a no-reward_choice group (NRC), and a no-reward_no-choice group (NRNC). Five participants' error rate went beyond 3 SD of the average error rate, two participants did not attend the retention test, and two participants failed to complete the questionnaire. Therefore, they were all removed from the data analysis. Finally, 110 participants were included in the data analysis (RC group: $n = 26$, 5 males, $M_{age} = 20.27$, SD = 2.48; RNC group: $n = 27$, 6 males, $M_{age} = 19.70$, SD = 1.77; NRC group: $n = 28$, 6 males, $M_{age} = 20.43$, SD = 2.91; NRNC group: $n = 29$, 6 males, $M_{age} = 20.05$, SD = 2.02). All the participants were right-handed, had normal or corrected-to-normal vision, and were free from neurological/physical disorders. The present study was approved by the ethics committee of Beijing Sport University. All participants were financially compensated at the end of the experiment.

2.2 Materials and equipment

Two fixed sequences with 12 elements were used in the present study: 3–4–2–3–1–2–1–4–3–2–4–1 (A sequence) and 1-2-1-4-2-3-4-1-3-2-4-3 (B sequence), where the numbers 1–4 represented four stimulus locations from left to right. These sequences were used in the previous study and were proved equal (Bo et al., 2011). The visual stimuli were presented on a 14.2-inch computer screen (refresh rate: 60 Hz). Experiments were run with Psychopy 2.1.2 (Peirce, 2007).

2.3 Procedure

The formal experiment consisted of six stages across 10 sessions: s1-S2-S3-S4-S5-S6-s7-r8-s9-s10. Specifically, s1 denoted the pre-test, S2-S6 denoted training sessions, s7 denoted the immediate post-test, r8 denoted a random session, s9 denoted the delayed post-test, and s10 denoted the retention test after 24 h. Within each session, a 12-element sequence was repeated six times, resulting in 72 trials per session. Participants would learn either sequence A or sequence B, which was presented in fixed-sequence sessions (sessions with the letter "s" or "S"). In each experimental group, half of the participants were assigned to learn sequence A, and the other half were assigned to learn sequence B. To prevent the development of explicit knowledge of the sequences, each fixed session started at a unique position within the sequence. In the random session (r8), the sequence was randomly generated.

In the pre-test, post-test, and retention test phases, all the participants completed the traditional version of SRTT without any feedback. At the beginning of each trial, four blank squares with white borders were displayed in a line in the center of the screen for 250 ms. Then one of the squares turned white, and participants were required to respond as quickly and accurately as possible by pressing the corresponding key (D: left middle finger, F: left index finger, J: right index finger, K: right middle finger). The target disappeared after the key press or lasted for 1,000 ms. There was an interval of 250 ms between each trial.

In the training phase, the choice phases and feedback phases were added to the SRTT for the manipulation of reward and voluntary choice. Participants were randomly assigned into four groups and trained under different experimental conditions. The training phase consisted of five sessions, with a sequence repeated six times per session. The choice phase was presented before the beginning of each 12-trial training session, resulting in a total of 30 times of occurrence until the end of the training phase. Specifically, a fixation point appeared in the center of the screen for 400 ms. Participants in the voluntary choice groups were instructed that in the next part, they could freely select a color by pressing the corresponding key ("R" for the left, "U" for the right). In contrast, participants in the forced choice groups were informed that the computer would randomly select a color for them. After the instruction, two squares with complementary colors (e.g., blue and yellow) were horizontally displayed on the screen. For participants in the voluntary choice groups, the time allowed for making choices was unlimited, and the same amount of time was used for computer selection in the forced choice groups. The selected color (e.g., blue) was displayed in the center of the screen for 1,000 ms and used as the target color in the following 12 trials.

For the manipulation of reward, participants in the reward groups were informed that the points gained in the training sessions would be converted into their final pay at the end of the experiment, while participants in the no-reward groups were informed that no reward would be given in the experiment. If the response was correct and faster than individual criterion RT, positive feedback was presented following the key press for 800 ms ("+10" for the reward groups, "+0" for the no-reward groups). The criterion RT was calculated as the mean RT in the pre-test. "Correct, too slow" was displayed when the response was correct but slower than the criterion RT. "Too slow!" was displayed when the key press was not made within 1,000 ms. "Wrong" was displayed if a key press error occurred. Considering the limited research funding and the potential negative impact of a small exchange rate on participants' motivation, participants in the reward groups were not informed of the specific exchange rate between points and money, and the total points they gained in the training sessions. After the experiment, the experimenter randomly selected one reward amount from 4, 5, or 6 (Chinese yuan), which was added to the basic payment (10 Chinese yuan). All participants accepted the final experimental payment without any questions. Figure 1 depicted a rewarded trial with the choice phase.

After the experiment, participants were required to complete a questionnaire consisting of five questions according to their feelings during the experiment. Participants rated on these items (1–7 indicated "entirely disagree – entirely agree"):

1. "I had the power to choose throughout the experiment";
2. "I was fully capable of the task";
3. "This task was very interesting";
4. "I was very satisfied with my performance throughout the experiment";
5. "I was nervous throughout the experiment."

2.4 Statistical analysis

The error rate was calculated as the proportion of incorrect trials and omissions. The mean error rate was 2.5% (SD = 2.2). ANOVAs conducted on error rates showed no significant effect for each session ($ps > 0.1$). Therefore, we focused on the analysis of RTs. For the analysis of correct RTs, trials with RT beyond 3 SD of the mean of each participant were excluded. Finally, 96.1% of trials were included in the statistical analysis of RTs.

Firstly, 2 (Reward: reward vs. no-reward) × 2 (Choice: choice vs. no-choice) ANOVAs were conducted on the mean RTs of the pre-test to determine if participants in the four conditions exhibited differences. Secondly, to examine the effects of reward and voluntary choice in the training session, we conducted a 2 (Reward) × 2 (Choice) × 5 (training sessions) repeated-measures ANOVA on RT. To further evaluate the training effect, we performed linear regressions across the five training sessions and extracted the slope of the regression fits for each participant to establish the learning rates. The slope values were analyzed using a two-way ANOVA (Reward × Choice). Thirdly, to explore the impact of reward and choice on motor skill performance, we

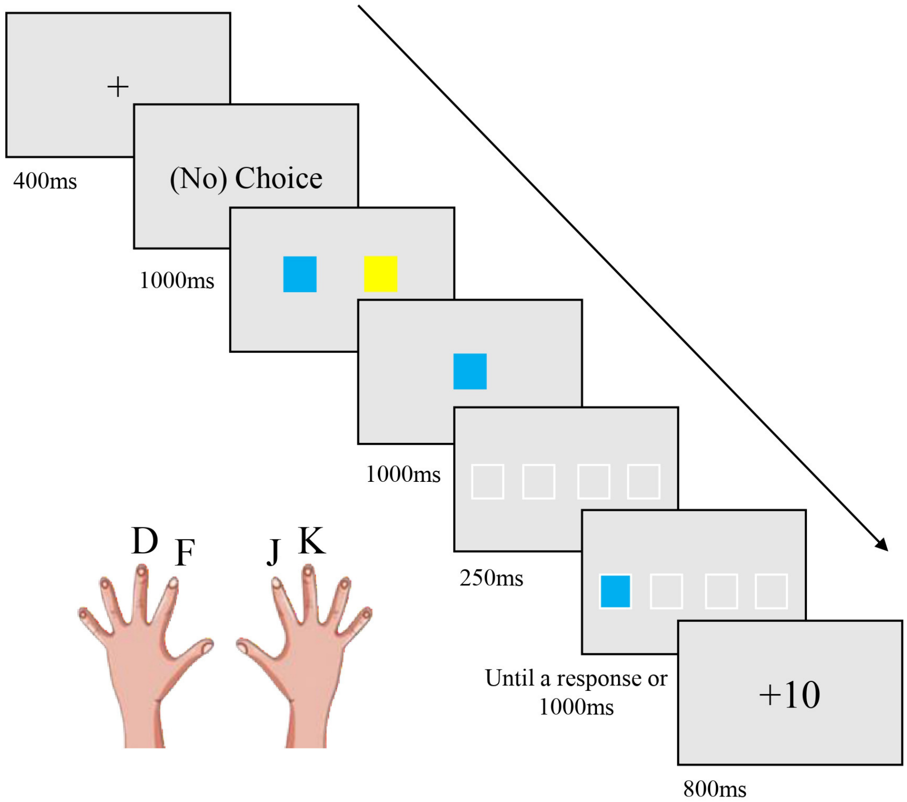

FIGURE 1
A rewarded trial with the choice phase during the training phase. The choice phases and feedback phases were added to the SRTT for the manipulation of reward and voluntary choice in the training phase.

explored GL, SSL, and retention effects by two-way ANOVAs. The GL effect was calculated by the RT difference between s1 and s7. The SSL effect was determined as the RT difference between r8 and the mean of s7 and s9. The retention effect was calculated by comparing s10 to s1. Finally, for analyses of the subjective report, two-way ANOVAs were conducted on each item of the questionnaire. Statistical analyses were performed using IBM SPSS 23.0 (IBMCorp., Armonk, N.Y., USA), and the alpha level was set at 0.05.

3 Results

3.1 Behavioral data

A two-way ANOVA conducted on mean RT of the pre-test did not show any significant main effects or interaction, *ps* > 0.16, suggesting that initial performance was comparable in different groups.

To examine the effects of reward and choice on the training phase, a repeated-measures ANOVA with reward and choice as between-subject factors and training session as a within-subject factor was conducted. The results revealed significant main effects of session, $F(4, 103) = 6.773$, $p < 0.001$, $\eta_p{}^2 = 0.208$, reward, $F(1, 106) = 6.864$, $p = 0.010$, $\eta_p{}^2 = 0.061$ and the interaction of reward and session, $F(4, 103) = 4.041$, $p = 0.004$, $\eta_p{}^2 = 0.136$. The main effect of choice was not significant, $F(1, 106) = 3.524$, $p = 0.063$, $\eta_p{}^2 = 032$. Simple effects analysis showed that only the reward groups showed significantly reduced RTs from S2 to S4, S5, and S6 (*ps* < 0.001), whereas no significant differences in the no-reward groups across the training process (*ps* > 0.1). In order to gain further insight into the training rates, linear regressions were performed on RTs obtained in five training blocks, and the slope of the fits was extracted for each participant. The slope values represented the rates of performance improvement and were analyzed using a 2 (Reward) × 2 (Choice) ANOVA. The results showed a significant main effect of reward, $F(1, 106) = 15.276$, $p < 0.001$, $\eta_p{}^2 = 0.126$. The slopes were steeper in the reward groups than in the no-reward groups, indicating that the reward groups improved faster than the no-reward groups. The main effect of choice and the interaction were not significant (*ps* > 0.13). Additionally, no differences were observed when comparing the intercepts of the reward and no-reward groups ($p = 0.078$), which indicated that the reward-induced training effect could not be explained by initial performance. Figure 2 illustrated the mean RT of each session for all groups.

For the general learning effect (see Figure 3A), no main effects and interaction were observed (*ps* > 0.15). For the sequence-specific learning effect (see Figure 3B), a main effect of reward was found, $F(1, 106) = 6.404$, $p = 0.013$, $\eta_p{}^2 = 0.057$, indicating that the reward groups have more sequence-specific enhancement than the no-reward groups. The main effect of choice was significant,

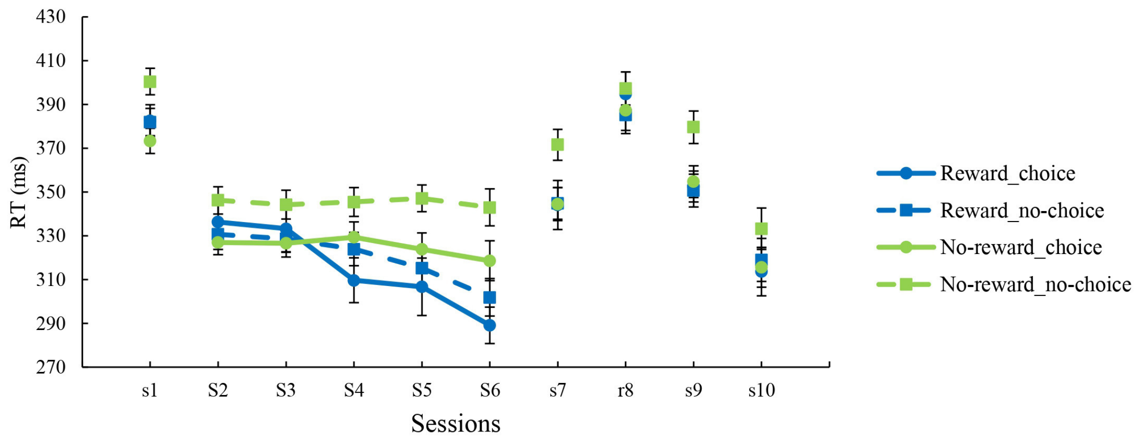

FIGURE 2
Mean reaction time for each group across all sessions. Displayed are the means ± SEM.

$F(1, 106) = 6.590$, $p = 0.012$, $\eta_p{}^2 = 0.059$, indicating that the choice groups have more sequence-specific enhancement than the no-choice groups. The interaction did not reach significance ($p = 0.456$). These results indicate that both reward and choice enhanced sequence-specific learning, but these two factors may work independently. Regarding the retention effect on day 2, no significant main effects or interaction were observed, $ps > 0.28$.

3.2 Subjective report

Participants in the choice groups reported higher autonomy than participants in the no-choice groups, evidenced by a main effect of choice on item 1, $F(1, 106) = 39.306$, $p < 0.001$, $\eta_p{}^2 = 0.271$, indicating the effective manipulation of choice. No significant effects of reward, choice, or their interaction were found on item 2 ($ps > 0.31$) or item 3 ($ps > 0.14$). A significant Reward × Choice interaction was found on item 4, $F(1, 106) = 4.240$, $p = 0.042$, $\eta_p{}^2 = 0.038$. Simple effects analysis showed that participants in the choice group were marginally more satisfied with their performance than participants in the no-choice group under the reward condition (5.54 ± 0.25 vs. 4.89 ± 0.24, $p = 0.064$), while no significant difference in the no-reward condition ($p = 0.223$). A significant Choice × Reward interaction on item 5 was observed, $F(1,106) = 5.605$, $p = 0.020$, $\eta_p^2 = 0.050$. Specifically, under the reward condition, participants with choice felt significantly less nervous than participants with no choice (2.85 ± 0.30 vs. 3.81 ± 0.30, $p = 0.025$), while there was no significant difference on nervousness under the no-reward condition ($p = 0.296$).

4 Discussion

In the present study, we employed the SRTT to investigate the impact of reward and voluntary choice on motor skill performance and learning. During the training phase, participants received manipulations of reward and voluntary choice. The results indicated that reward and voluntary choice significantly enhanced the sequence-specific learning effect, yet no interaction was observed. Neither reward nor voluntary choice affected GL and retention with an interval of 24 h. These findings suggest that reward and voluntary choice may benefit motor skill performance at the action-selection level through independent ways, which implies different mechanisms underlying the influences of reward and voluntary choice.

The facilitating effect of reward was found on the sequence-specific learning effect, which was consistent with the findings of Wächter et al. (2009). In the present study, the reward groups received performance-contingent monetary rewards during the training phase. The beneficial effect of reward was observed in the training phase, and extended to post-training performance indexed by sequence-specific learning. Although the performance of the SRTT is often constrained by speed-accuracy trade-off, reward has been demonstrated to be a strong motivational factor, which could improve both speed and accuracy of movements (i.e., better performance) (Manohar et al., 2015). Evidence from neuroimaging studies showed that individuals exhibited stronger neural activity in striatum during motor skill training with reward (Doppler et al., 2019; Widmer et al., 2016). Such reward modulation on motor adjustments has been shown to be dependent on dopamine (Schultz, 1998), a key neurotransmitter that carries the reward signal. Experiencing reward as well as the desire for rewarding stimuli, elicits dopamine activity, which directs attention to valuable cues and induces motivation to obtain reward (Ferguson et al., 2020; Knowlton and Castel, 2022; Schultz, 2010, 2013). However, reward did not enhance the general learning effect. General learning indicated faster response irrespective of sequence structure. In contrast, sequence-specific learning encompassed both implicit sequence knowledge and key-pressing execution. In the post-tests participants performed without reward. Therefore, it is possible that reaction-based performance (i.e., general learning) decayed since each fast response was not reinforced in time, while sequence-based performance (i.e., sequence-specific learning) was improved since rewarded participants may have encoded sequence knowledge during the training phase.

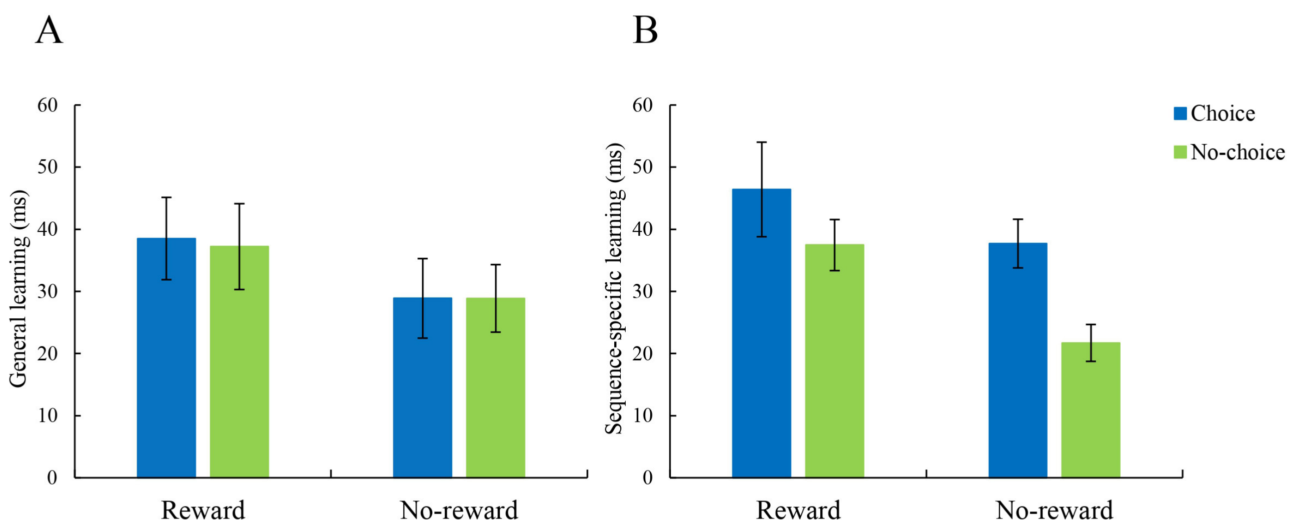

FIGURE 3
(A) General learning effects under different conditions. No main effects or interaction was observed. The choice condition is shown in blue, the no-choice condition is shown in green. **(B)** Sequence-specific learning effects under different conditions. There was a significant main effect of reward and voluntary choice on SSL, indicating that the reward groups gained more sequence-specific learning effects than the no-reward groups and that the choice groups gained more sequence-specific learning effects than the no-choice groups. No interaction of reward and choice was observed. Displayed are the means ± SEM.

Although reward boosted immediate skill performance, it did not enhance retention, which aligns with previous studies on the SRTT (Doppler et al., 2019; Steel et al., 2016). Retention of motor skills is influenced by multiple factors, including the length of the retention interval, activities performed during the interval and sleep (Cohen et al., 2005). In the present study, we did not restrict the retention interval to exactly 24 h, nor did we control for the periods of sleep and wakefulness, or measure the quality of sleep and other activities during the interval, which may potentially affect the results of retention.

Voluntary choice was found to benefit the sequence-specific learning effect but had no impact on skill retention. Previous research has shown that following the making of a task-irrelevant choice, participants exhibited improved motor skill learning at the execution level indexed by enhanced performance in the retention and transfer test (Lewthwaite et al., 2015; Wulf et al., 2014). For example, in a ball-throwing task, participants who were given the opportunity to choose the ball color during practice showed higher throwing accuracy in retention and transfer tests than the control group (Wulf et al., 2014). Providing choice has been suggested to allow a feeling of autonomy, which enhances intrinsic motivation to focus on the task goal, leading to superior motor performance and learning (Wulf and Lewthwaite, 2016). However, our results showed that voluntary choice improved immediate motor performance on day 1, but had no facilitating effect on the skill retention. Skill retention was calculated by the difference between the first session on day 1 and the session on day 2, which were both sequence sessions. Thus, retention may only reflect response-based RT savings similar to general learning. Since the choice effect was not found on general learning, it may not extend to retention. Another possible explanation was that when the subsequent task primarily involves action execution that relies on muscle commands (e.g., golf-putting task), the effect of voluntary choice may be more pronounced and profound. In the present study, we used the SRTT, which mainly focuses on the selection process of motor skill learning (Diedrichsen and Kornysheva, 2015; Rowland and Shanks, 2006). Compared to action execution, action selection is more of a cognitive process involving complex internal mechanisms and higher-order information processing, which may be more susceptible to choice effect during online practice than offline consolidation.

Although both reward and voluntary choice facilitated sequence-specific learning, no combined effect of reward and voluntary choice was observed. It is possible that these two factors may influence the training processes in different ways. According to the results of the training phase, reward enhanced SRTT performance during the training phase. Receiving performance-dependent reward may reinforce accurate motor responses, thereby fostering motor-based implicit memory. Therefore, an effect of reward was observed on sequence-specific learning. Voluntary choice did not affect the SRTT performance during the training phase, whereas did have an impact on subsequent sequence-specific learning. In our study, participants in the choice groups could choose the color of target stimuli, which was irrelevant to the task, while participants in the no-choice groups were yoked to their counterparts in the choice groups. Autonomy provided by voluntary choice may increase task engagement and attention to the sequential stimuli, which may further positively influence the encoding of the sequence. Thus, an effect of voluntary choice was observed on sequence-specific learning.

Finally, a limitation of the current study is that motivation was not measured directly in any way before and after the experiment. It has been shown that the initial level of motivation affects the impact of voluntary choice on motor skill learning (Ikudome et al., 2019). In Ikudome and colleagues' study, participants were divided into two groups according to their levels of intrinsic motivation for the dart-throwing task in a preliminary experiment. In the formal experiment, some participants in each group could choose the dart color, while others were yoked to their counterparts. Results showed that voluntary choice had a positive effect on skill learning in the less motivated participants, but not in the highly motivated ones. Additionally, the lack of measurement on extrinsic and intrinsic motivation prevented the elucidation of the relative change of two types of motivation during the experiment. Further studies are needed to match the experimental groups based on motivation and to measure motivation levels to clarify the underlying mechanism. Another issue that needs to be addressed is that when calculating the sample size, we referred to an effect size estimated from only published self-controlled learning experiments ($g = 0.54$), which was slightly higher than the overall estimate ($g = 0.44$) reported by McKay et al. (2022). In the present study, the findings indicated moderate effect size of reward and choice ($\eta_p{}^2 = 0.057$–0.061), which was higher than the overall estimate, although lower than we expected. We included 110 participants in the final data analysis, with at least 26 participants in each experimental group. This was a reasonable sample size given that typically small sample sizes in motor learning studies (Lohse et al., 2016). Nevertheless, future studies should use more appropriate sample sizes to obtain reliable results.

In conclusion, the present study aimed to examine whether reward and voluntary choice have a combined effect on motor skill learning. The results demonstrated that reward and voluntary had positive impacts on sequence-specific learning, whereas no interaction was observed. Both reward and voluntary choice failed to benefit skill retention. These findings suggest that reward and voluntary choice enhance motor skill performance independently, potentially at the action-selection level, which implies different mechanisms underlying the influences of reward and voluntary choice.

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/ejhfr/.

Ethics statement

The studies involving humans were approved by Ethics Approval Form for Sports Science Experiments of Beijing Sport 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

YQ: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. JW: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Formal analysis. YW: Data curation, Writing – original draft, Formal analysis. GK: Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing, Formal analysis.

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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.

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References

Abe, M., Schambra, H., Wassermann, E. M., Luckenbaugh, D., Schweighofer, N., and Cohen, L. G. (2011). Reward improves long-term retention of a motor memory through induction of offline memory gains. *Curr. Biol.* 21, 557–562. doi: 10.1016/j.cub.2011.02.030

An, J., Chua, L. K., and Wulf, G. (2020). Optimising golf putting. *Int. J. Sport Exerc. Psychol.* 19, 882–894. doi: 10.1080/1612197X.2020.1854823

Anderson, S. P., Adkins, T. J., Gary, B. S., and Lee, T. G. (2020). Rewards interact with explicit knowledge to enhance skilled motor performance. *J. Neurophysiol.* 123, 2476–2490. doi: 10.1152/jn.00575.2019

Bacelar, M. F. B., Lohse, K. R., and Miller, M. W. (2020). The effect of rewards and punishments on learning action selection and execution components of a motor skill. *J. Mot. Learn Dev.* 8, 475–496. doi: 10.1123/jmld.2019-0039

Bo, J., Jennett, S., and Seidler, R. D. (2011). Working memory capacity correlates with implicit serial reaction time task performance. *Exp. Brain Res.* 214, 73–81. doi: 10.1007/s00221-011-2807-8

Carter, M. J., Carlsen, A. N., and Ste-Marie, D. M. (2014). Self-controlled feedback is effective if it is based on the learner's performance: a replication and extension of Chiviacowsky and Wulf (2005). *Front. Psychol.* 5:1325. doi: 10.3389/fpsyg.2014.01325

Chelazzi, L., Perlato, A., Santandrea, E., and Della Libera, C. (2013). Rewards teach visual selective attention. *Vision Res.* 85, 58–72. doi: 10.1016/j.visres.2012.12.005

Cohen, D. A., Pascual-Leone, A., Press, D. Z., and Robertson, E. M. (2005). Off-line learning of motor skill memory: a double dissociation of goal and movement. *Proc. Natl. Acad. Sci. U.S.A.* 102, 18237–18241. doi: 10.1073/pnas.0506072102

Deci, E. L., and Ryan, R. M. (1987). The support of autonomy and the control of behavior. *J. Pers. Soc. Psychol.* 53, 1024–1037. doi: 10.1037/0022-3514.53.6.1024

Diedrichsen, J., and Kornysheva, K. (2015). Motor skill learning between selection and execution. *Trends Cogn. Sci.* 19, 227–233. doi: 10.1016/j.tics.2015.02.003

Doppler, C. E. J., Meyer, L., Dovern, A., Stühmer-Beckh, J., Weiss, P. H., and Fink, G. R. (2019). Differential impact of social and monetary reward on procedural learning and consolidation in aging and its structural correlates. *Front. Aging Neurosci.* 11:188. doi: 10.3389/fnagi.2019.00188

Dovern, A., Fink, G. R., Saliger, J., Karbe, H., Koch, I., and Weiss, P. H. (2011). Apraxia impairs intentional retrieval of incidentally acquired motor knowledge. *J. Neurosci.* 31, 8102–8108. doi: 10.1523/jneurosci.6585-10.2011

Ferguson, L. M., Ahrens, A. M., Longyear, L. G., and Aldridge, J. W. (2020). Neurons of the ventral tegmental area encode individual differences in motivational "wanting" for reward cues. *J. Neurosci.* 40, 8951–8963. doi: 10.1523/jneurosci.2947-19.2020

Grand, K. F., Daou, M., Lohse, K. R., and Miller, M. W. (2017). Investigating the mechanisms underlying the effects of an incidental choice on motor learning. *J. Mot. Learn. Dev.* 5, 207–226. doi: 10.1123/jmld.2016-0041

Grehl, M. M., Mehta, M., Morris, L. S., Rutter, S. B., and Westwater, M. L. (2022). On what motivates us: a detailed review of intrinsic *v.* extrinsic motivation. *Psychol. Med.* 52, 1801–1816. doi: 10.1017/S0033291722001611

Ikudome, S., Kou, K., Ogasa, K., Mori, S., and Nakamoto, H. (2019). The effect of choice on motor learning for learners with different levels of intrinsic motivation. *J. Sport Exerc. Psychol.* 41, 159–166. doi: 10.1123/jsep.2018-0011

Iwatsuki, T., and Otten, M. P. (2020). Providing choice enhances motor performance under psychological pressure. *J. Mot. Behav.* 53, 656–662. doi: 10.1080/00222895.2020.1833827

Kang, G., Chang, W., Wang, L., and Zhou, X. (2019). Reward expectation modulates multiple stages of auditory conflict control. *Int. J. Psychophysiol.* 146, 148–156. doi: 10.1016/j.ijpsycho.2019.09.009

Kang, G., Luo, X., Chen, L., Chen, J., Chen, J., Dai, H., et al. (2024). Reward delays quitting in visual search. *Psychol. Res.* 88, 404–416. doi: 10.1007/s00426-023-01860-6

Keetch, K. M., and Lee, T. D. (2007). The effect of self-regulated and experimenter-imposed practice schedules on motor learning for tasks of varying difficulty. *Res. Q. Exerc. Sport* 78, 476–486. doi: 10.1080/02701367.2007.10599447

Kim, H. E., Avraham, G., and Ivry, R. B. (2021). The psychology of reaching: action selection, movement implementation, and sensorimotor learning. In S. T. Fiske (Ed.). *Annu. Rev. Psychol.* 72, 61–95. doi: 10.1146/annurev-psych-010419-051053

Knowlton, B. J., and Castel, A. D. (2022). Memory and reward-based learning: a value-directed remembering perspective. *Annu. Rev. Psychol.* 73, 25–52. doi: 10.1146/annurev-psych-032921-050951

Lewthwaite, R., Chiviacowsky, S., Drews, R., and Wulf, G. (2015). Choose to move: the motivational impact of autonomy support on motor learning. *Psychon. Bull. Rev.* 22, 1383–1388. doi: 10.3758/s13423-015-0814-7

Lohse, K. R., Buchanan, T. L., and Miller, M. W. (2016). Underpowered and overworked: problems with data analysis in motor learning studies. *J. Mot. Learn Dev.* 4, 37–58. doi: 10.1123/jmld.2015-0010

Luo, X., Wang, L., and Zhou, X. (2022). Belief in control: voluntary choice enhances subsequent task performance under undefeated choice-outcome causation. *Cognition* 225:105108. doi: 10.1016/j.cognition.2022.105108

Luo, X., Wang, L., and Zhou, X. (2024). Volition motivates cognitive performance at the response-execution level by attenuating task-irrelevant motor activations. *Cognition* 245:105738. doi: 10.1016/j.cognition.2024.105738

Manohar, S. G., Chong, T. T., Apps, M. A., Batla, A., Stamelou, M., Jarman, P. R., et al. (2015). Reward pays the cost of noise reduction in motor and cognitive control. *Curr. Biol.* 25, 1707–1716. doi: 10.1016/j.cub.2015.05.038

Martinez, V. M. L., Cardozo, P., Kaefer, A., Wulf, G., and Chiviacowsky, S. (2024). Positive feedback enhances motivation and skill learning in adolescents. *Learn. Motiv.* 86:101966. doi: 10.1016/j.lmot.2024.101966

McKay, B., Bacelar, M. F. B., Parma, J. O., Miller, M. W., and Carter, M. J. (2023). The combination of reporting bias and underpowered study designs has substantially exaggerated the motor learning benefits of self-controlled practice and enhanced expectancies: a meta-analysis. *Int. Rev. Sport Exerc. Psychol.* 2023, 1–21. doi: 10.1080/1750984X.2023.2207255

McKay, B., and Ste-Marie, D. M. (2020a). Autonomy support and reduced feedback frequency have trivial effects on learning and performance of a golf putting task. *Hum. Mov. Sci.* 71:102612. doi: 10.1016/j.humov.2020.102612

McKay, B., and Ste-Marie, D. M. (2020b). Autonomy support via instructionally irrelevant choice not beneficial for motor performance or learning. *Res. Q. Exerc. Sport* 93, 64–76. doi: 10.1080/02701367.2020.1795056

McKay, B., Yantha, Z. D., Hussien, J., Carter, M. J., and Ste-Marie, D. M. (2022). Meta-analytic findings of the self-controlled motor learning literature: underpowered, biased, and lacking evidential value. *Meta-Psychology* 6:2803. doi: 10.15626/MP.2021.2803

Meier, B., and Cock, J. (2014). Offline consolidation in implicit sequence learning. *Cortex* 57, 156–166. doi: 10.1016/j.cortex.2014.03.009

Palminteri, S., Lebreton, M., Worbe, Y., Hartmann, A., Lehéricy, S., Vidailhet, M., et al. (2011). Dopamine-dependent reinforcement of motor skill learning: evidence from Gilles de la Tourette syndrome. *Brain* 134, 2287–2301. doi: 10.1093/brain/awr147

Parma, J. O., Miller, M. W., and Bacelar, M. F. B. (2024). OPTIMAL theory's claims about motivation lack evidence in the motor learning literature. *Psychol. Sport Exerc.* 74:102690. doi: 10.1016/j.psychsport.2024.102690

Peirce, J. W. (2007). PsychoPy–Psychophysics software in Python. *J. Neurosci. Methods* 162, 8–13. doi: 10.1016/j.jneumeth.2006.11.017

Post, P. G., Fairbrother, J. T., and Barros, J. A. C. (2011). Self-controlled amount of practice benefits learning of a motor skill. *Res. Q. Exerc. Sport* 82, 474–481. doi: 10.1080/02701367.2011.10599780

Post, P. G., Fairbrother, J. T., Barros, J. A. C., and Kulpa, J. D. (2014). Self-controlled practice within a fixed time period facilitates the learning of a basketball set shot. *J. Mot. Learn Dev.* 2, 9–15. doi: 10.1123/jmld.2013-0008

Rowland, L. A., and Shanks, D. R. (2006). Sequence learning and selection difficulty. *J. Exp. Psychol. Hum. Percept. Perform.* 32, 287–299. doi: 10.1037/0096-1523.32.2.287

Ryan, R. M., and Deci, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *Am. Psychol.* 55, 68–78. doi: 10.1037/0003-066x.55.1.68

Sanli, E. A., Patterson, J. T., Bray, S. R., and Lee, T. D. (2013). Understanding self-controlled motor learning protocols through the self-determination theory. *Front. Psychol.* 3:611. doi: 10.3389/fpsyg.2012.00611

Schultz, W. (1998). Predictive reward signal of dopamine neurons. *J. Neurophysiol.* 80, 1–27. doi: 10.1152/jn.1998.80.1.1

Schultz, W. (2006). Behavioral theories and the neurophysiology of reward. *Annu. Rev. Psychol.* 57, 87–115. doi: 10.1146/annurev.psych.56.091103.070229

Schultz, W. (2010). Dopamine signals for reward value and risk: basic and recent data. *Behav. Brain Funct.* 6:24. doi: 10.1186/1744-9081-6-24

Schultz, W. (2013). Updating dopamine reward signals. *Curr. Opin. Neurobiol.* 23, 229–238. doi: 10.1016/j.conb.2012.11.012

Steel, A., Silson, E. H., Stagg, C. J., and Baker, C. I. (2016). The impact of reward and punishment on skill learning depends on task demands. *Sci. Rep.* 6:36056. doi: 10.1038/srep36056

St. Germain, L., McKay, B., Poskus, A., Williams, A., Leshchyshen, O., Feldman, S., et al. (2023). Exercising choice over feedback schedules during practice is not advantageous for motor learning. *Psychon. Bull. Rev.* 30, 621–633. doi: 10.3758/s13423-022-02170-5

St. Germain, L., Williams, A., Balbaa, N., Poskus, A., Leshchyshen, O., Lohse, K. R., et al. (2022). Increased perceptions of autonomy through choice fail to enhance motor skill retention. *J. Exp. Psychol. Hum. Percept. Perform.* 48, 370–379. doi: 10.1037/xhp0000992

Sugawara, S. K., Tanaka, S., Okazaki, S., Watanabe, K., and Sadato, N. (2012). Social rewards enhance offline improvements in motor skill. *PLoS ONE* 7:e48174. doi: 10.1371/journal.pone.0048174

Vassiliadis, P., Derosiere, G., Dubuc, C., Lete, A., Crevecoeur, F., Hummel, F. C., et al. (2021). Reward boosts reinforcement-based motor learning. *iScience* 24:102821. doi: 10.1016/j.isci.2021.102821

Wächter, T., Lungu, O. V., Liu, T., Willingham, D. T., and Ashe, J. (2009). Differential effect of reward and punishment on procedural learning. *J. Neurosci.* 29, 436–443. doi: 10.1523/jneurosci.4132-08.2009

Widmer, M., Ziegler, N., Held, J., Luft, A., and Lutz, K. (2016). Rewarding feedback promotes motor skill consolidation via striatal activity. *Prog. Brain Res.* 229, 303–323. doi: 10.1016/bs.pbr.2016.05.006

Wulf, G., Chiviacowsky, S., and Cardozo, P. L. (2014). Additive benefits of autonomy support and enhanced expectancies for motor learning. *Hum. Mov. Sci.* 37, 12–20. doi: 10.1016/j.humov.2014.06.004

Wulf, G., Clauss, A., Shea, C. H., and Whitacre, C. A. (2001). Benefits of self-control in dyad practice. *Res. Q. Exerc. Sport* 72, 299–303. doi: 10.1080/02701367.2001.10608964

Wulf, G., Iwatsuki, T., Machin, B., Kellogg, J., Copeland, C., and Lewthwaite, R. (2018). Lassoing skill through learner choice. *J. Mot. Behav.* 50, 285–292. doi: 10.1080/00222895.2017.1341378

Wulf, G., and Lewthwaite, R. (2016). Optimizing performance through intrinsic motivation and attention for learning: the OPTIMAL theory of motor learning. *Psychon. Bull. Rev.* 23, 1382–1414. doi: 10.3758/s13423-015-0999-9

Yadav, G., and Duque, J. (2023). Reflecting on what is "skill" in human motor skill learning. *Front. Hum. Neurosci.* 17:1117889. doi: 10.3389/fnhum.2023.1117889

Zhao, J., Zhang, G., and Xu, D. (2024). The effect of reward on motor learning: different stage, different effect. *Front. Hum. Neurosci.* 18:1381935. doi: 10.3389/fnhum.2024.1381935

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Effects of mental fatigue on perception of effort and performance in national level swimmers

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Objective: This study aimed to investigate the effects of mental fatigue on the perceptual and physiological responses to swimming at the lactate threshold (LT) and on 400-m front-crawl performance.

Methods: Ten national-level swimmers were tested three separate times. In the first session, swimmers performed a 7x200-m incremental test for LT assessment. In sessions two and three, participants performed the AX-Continuous Performance Task for 90-min (mental fatigue condition) or rested for 90-min (control condition) in a randomized and counterbalanced order. After the experimental manipulation, the participants performed a 12x100-m constant-speed test at LT followed by a 400-m front-crawl performance test. Fatigue was measured using the Brunel Mood Scale before and after the experimental manipulation. Heart rate (HR), blood lactate concentration (La) and rating of perceived exertion (RPE) were measured during the swimming tests. Generalized Mixed Models were used to test main effects and interactions, and Holm-Bonferroni post-hoc correction was applied when necessary ($p < 0.05$).

Results: Fatigue increased only for the mental fatigue condition ($p = 0.018$). During the 12 x 100 m constant-speed test at LT, athletes in the mental fatigue condition presented higher RPE ($p = 0.001$) despite similar HR and La responses compared to control. Performance in the 400-m front-crawl test was significantly impaired in mentally fatigued swimmers ($p < 0.001$).

Conclusion: These findings show that mental fatigue increases the perception of effort during swimming at LT despite no significant physiological alterations and reduces 400-m front-crawl performance in national level swimmers.

KEYWORDS

cognitive effort, self-regulation, rating of perceived exertion, swimming, performance

Introduction

Traditionally, the study of fatigue in swimming and other sports has focused primarily on the cardiorespiratory, central and peripheral mechanisms of muscle fatigue defined as the exercise-induced reduction in maximal voluntary force or power output of the locomotor muscles (Amann and Dempsey, 2008; Buoite Stella et al., 2024; Yoma et al., 2020). However, coaches and athletes often complain about the negative effects of another kind of fatigue, commonly called mental fatigue (Russell et al., 2019). This is not surprising if we consider that sport is one of the most cognitively and emotionally demanding activities performed by humans (Walsh, 2014). Furthermore, athletes are exposed to various additional psychological stressors related to the sport organization and their personal lives (Mellalieu et al., 2021).

Mental fatigue has been defined as the psychobiological state induced by sustained cognitive effort (Marcora et al., 1985) and it is revealed by subjective feelings of tiredness and lack of energy, brain alterations and impaired cognitive function (Cutsem and Marcora, 2021). Despite plenty of anecdotal evidence from coaches and athletes about the negative effects of mental fatigue on sport performance, only recently researchers has started to investigate this phenomenon (Marcora et al., 1985). The experimental evidence accumulated over the past 15 years suggests that mental fatigue negatively affects endurance performance, cognitive function, technical and tactical performance in physically active subjects and athletes (Cutsem and Marcora, 2021; Habay et al., 2021).

With specific reference to swimming, a study with young swimmers observed a reduction in 1500-m freestyle performance following a 30-min Stroop task in 12 of 16 athletes (Penna et al., 2018). According to the pacing analysis, the participants were slower in the mental fatigue condition in each 300-m split (i.e., 300, 600, 900, 1,200, and 1,500-m). In another study, international-level athletes (FINA score = 616 ± 28) used social media for 30 min to induce mental fatigue, and the effects on the 50, 100, and 200-m freestyle performance were observed (Fortes et al., 2020). For the 50-m race, mental fatigue presented no effect, which is expected for a race that lasts less than 30 s. On the other hand, the races of 100 and 200-m presented a negative effect of mental fatigue. However, the negative effect of mental fatigue on 200-m freestyle performance was not replicated by Quagliarotti et al. (2023) in a group of triathletes. Therefore, more research is needed to confirm the negative effects of mental fatigue on swimming endurance performance. Furthermore, the effects of mental fatigue on the cardiorespiratory, metabolic, biomechanical and perceptual determinants of endurance performance in swimmers are poorly understood.

To fill this gap in the research literature, the first aim of the present study was to investigate the effects of mental fatigue on the heart rate (HR), blood lactate concentration (La) and rating of perceived exertion (RPE) responses to swimming at the lactate threshold (LT). The second aim of the present study was to investigate further the effect of mental fatigue on endurance performance, which was measured with a 400-meter front-crawl test on a group of national-level swimmers. Based on previous findings in other sports (Marcora et al., 1985), we hypothesized (i) a significant increase in perception of effort despite no major cardiovascular and metabolic alterations during swimming at a constant speed, and (ii) a significant reduction in 400-m front-crawl performance in mentally fatigued swimmers.

Materials and methods

Participants

As inclusion criteria, participants had to be adult athletes with experience in national or international championships, free from neuromuscular and skeletal muscle injuries or disorders and clear from drugs or medications that could affect physical performance. The participants were excluded if they missed the experimental sessions or refused to follow the study recommendations. Before taking part in the study, all subjects were required to give their written informed consent once the experimental procedures, associated risks, and potential benefits of participation had been explained. The study procedures were approved by the University of Bologna's Bioethics Committee (protocol: 0126835 from 07/05/2024).

We estimated that 10 participants produced a power of $CI_{95\%} = 0.990$ (0.749–1.00) for the Generalized Mixed Model test. We calculated the power of the study using the app GLIMMPSE[1]. The calculus was made as follows: (a) Hotelling Lawley Trace test; (b) type one error rate of 0.05; (c) 400-m performance as the primary outcome; (d) repeated measures for condition (i.e., MF x CON); (e) no clustering was added to the analysis; (f) no fixed predictors were added; (g) no Gaussian covariate was added; (h) hypothesis contrast of all mean differences zero; (i) theta of zero; (j) smallest group size of 10; (k) marginal means of the CON (i.e., 277-s) and MF (i.e., 288-s) conditions; (l) scale factor for the marginal of 1; (m) standard deviation of 3.2; (n) repeated measure standard deviation ratios of 1 and 2; (o) repeated measure correlation with an unstructured matrix; and (p) scale factor variance of 1.

Study design

The experiment was a single-blind, randomized, counterbalanced AB/BA crossover study with A being the mental fatigue condition and B the control condition. In addition, time (pre and post experimental manipulation) or distance (400, 800, and 1,200-m during the 12 × 100-m constant-speed test) were included as within-subject factors when relevant. Participants were tested three times at the pool where they regularly trained with at least 7 days intervals between testing sessions. During the first session participants were familiarized with all study procedures and performed the 7 × 200-m incremental test to assess LT (see *Swimming tests* section for more details). In the following two sessions, participants performed either the AX-Continuous Performance Task for 90-min (mental fatigue condition) or rested for 90-min (control condition) in the allocated order. Mood was measured before and after the experimental manipulation (see *Experimental manipulation* section for more details). Subsequently, the participants performed the 12 × 100-m constant-speed test followed by the 400-m front-crawl performance test (Penna et al., 2018). During the swimming tests, HR, La and RPE were measured (see *Swimming tests* section for more details). The sessions were planned and organized according to the head coach and their seasonal plan mesocycle to ensure that swimmers received the same training and avoided strenuous exercise sessions 48 h before experimental procedures. All the sessions took place between January and February. An overview of the study design is shown in Figure 1.

Experimental manipulation

Randomization

The participants were randomly assigned to two conditions: mental fatigue and control in a random and counterbalanced order. They were randomized using a random number table with a 1:1 allocation ratio. The allocation was concealed from the researcher who enrolled and assessed participants, and only after the baseline tests, the allocation took place. The researcher who performed the post-intervention measurements was unaware of the condition the participant was allocated to (single blind).

1 https://glimmpse.samplesizeshop.org/

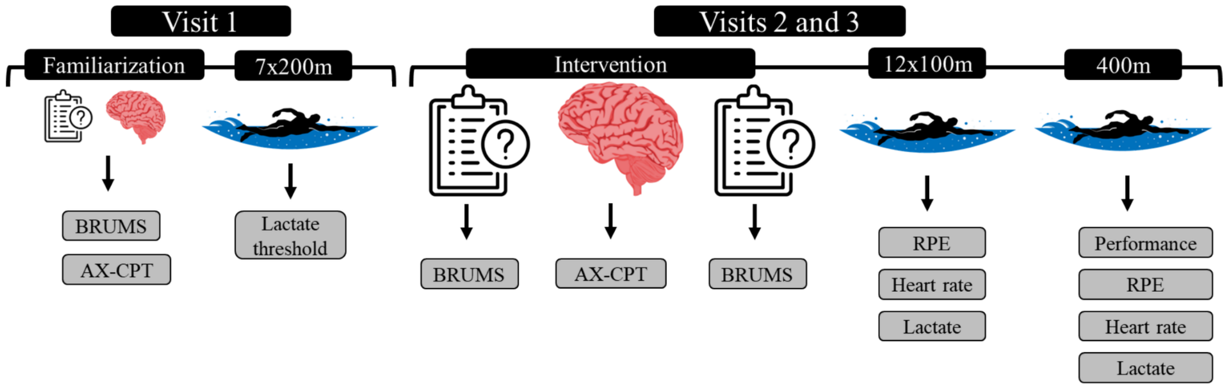

FIGURE 1
Experimental design of the study. BRUMS = Brunel mood scale; AX-CPT = AX-continuous performance test; RPE = rating of perceived exertion.

Mental fatigue condition

The AX-CPT was used to induce mental fatigue. The task was performed in a silent and bright room, with the participants comfortably sitting on a chair in front of a monitor and wearing an earphone auditive damper to avoid distractions. In this task (Marcora et al., 1985), a sequence of letters, one at a time, was presented to the participants on a computer screen. In front of a response box, participants were instructed to use the mouse and press the right button on target trials and the left button otherwise. The letter "A" appeared as the cue and the "X" as the probe, and the remaining letters served as invalid cues and nontarget probes. The sequences were pseudorandom, with the target (AX) occurring in 70% and nontarget 30% of the time. The letters were centrally presented on a black background for 300 ms in a 24-point Helvetica font, and a 1,200-ms interval followed each letter. A bleep warned the participants when they missed or gave an incorrect response.

Control condition

The participants remained in a room for 90-min without any cognitive stimuli. A researcher remained in the experimental room during the task to ensure the subject's followed the protocol.

Manipulation check

Participants responded to the Brunel Mood Scale (BRUMS) (Terry et al., 2003) to assess mood before and after the interventions. The BRUMS consists of 24 items divided into six subscales: anger, fatigue, depression, confusion, vigor, and tension. A Likert scale (5-point) provides a score that ranges from zero to sixteen for each subscale (four items per sub-scale). Based on the mental fatigue phenomenon, only fatigue and vigor subscales were analyzed for the study, as previously used in another study (Marcora et al., 1985).

Swimming tests

7 × 200-m incremental test

The 7 × 200-m test consisted of seven even-paced swims graded from easy to maximal and performed on a 5-min cycle (Pyne, 2001). Target times were calculated before testing based on 200-m personal best times used as the seventh step's target time. The target time for the first step was 30-s slower than the target time for the seventh step, with each intermediate step being completed at a speed that is a 5-s faster than the previous step. Each 100-m split and the total 200-m time were timed manually and had to be within 2 s of each other. Blood samples of 5 μL were taken from the earlobe for La analysis (Lactate Pro LT-1710, Arkray, Shiga, Japan) within a 1-min of completion of the swim for the first six efforts and 3 min after the final maximal effort. The anaerobic threshold (AT) was calculated using the D-max procedure (Bishop et al., 1998).

12 × 100-m constant-speed test

A standard warm-up was conducted before the 12 × 100 m. The warm-up consisted of a 300-m front crawl, a 100-m kick front crawl with a kickboard, a 100-m pull with a pull buoy, and a 100-m swim on the front crawl.

Subsequently participants completed one set of twelve 100-m front crawl swims at the speed corresponding to the lactate threshold, with 30 s of rest between repetitions. The hundreds of meters repetitions were performed every fixed time (turnaround), which was the sum of the pace to maintain during their swimming plus the rest (e.g., if the swimmer swam in 1-min and 10-s, with the 30-s rest, the turnaround was 1-min 40-s). Before the start of the test and at the end of the fourth, eighth, and twelfth 100-m repetition, HR was recorded (V800, Polar, Kempele, Finland) and participants were asked to rate their perception of effort using a large 6–20 Borg RPE scale following standard instructions (Pageaux and Lepers, 2016). At the same time, a blood sample of 5 μL was taken from the earlobe for La analysis.

Statistical analysis

The Generalized Mixed Models (GLzMM) analyzed the main effects and interaction between condition (i.e., control × mental fatigue), time (i.e., pre and post), and distance (i.e., pre, 400-m, 800-m, 1,200-m) for the manipulation check (BRUMS), 12 × 100 test, and 400-m performance. The GLzMM set up as follows: (a) subjects, condition, time, distance, and interactions were tested in the model as random effects; (b) condition, time, and distance as the within-subject variables; (c) Gamma or Gaussian distributions with identity link function for model type; (d) condition, time, and distance as factors; (e) Akaike Information Criterion for the better-fit model; (f) Wald chi-square statistics as the model effects; (g) Holm post-hoc for pairwise comparisons; and (h) graphic analysis of the residuals (Liang and Zeger, 1986). The data are presented in mean and 95% confidence interval of the mean. In case of significant results, the 95% confidence interval of the mean differences (CI95%diff) is presented. The analyses were made using JAMOVI v2.5.3.0.

Results

Participants flow

Ten swimmers, six men and four women were recruited to participate in the study and completed it (Table 1). The women in the study were absent from their normal cycle (i.e., amenorrhea). The swimmers were ranked in the top ten nationally in their respective events, with six having competed internationally. No participants were excluded throughout the study.

Manipulation check

BRUMS-vigor

We observed no condition ($X^2_{(1,9)} = 0.4$ $p = 0.526$) and interaction effects ($X^2_{(1,18)} = 3.5$ $p = 0.061$). There was however a significant reduction in vigor over time ($X^2_{(1,10)} = 4.7$ $p = 0.029$), as seen in Figure 2a.

BRUMS-fatigue

We observed no condition ($X^2_{(1,9)} = 1.47$ $p = 0.225$) effect. Significant results were find for time ($X^2_{(1,10)} = 7.11$ $p = 0.008$) and interaction ($X^2_{(1,18)} = 5.60$ $p = 0.018$). We observed increased fatigue following the mental fatigue intervention [PRE = 9.7 (8.3 to 11.1) a.u.; POST = 12.1 (9.7 to 14.6) a.u.; $CI_{95\%diff} = -2.43$ (−4.03 to −0.82); p = 0.018], while in CON fatigue did not change significantly [PRE = 9.0 (5.8 to 12.1) a.u.; POST = 8.6 (5.9 to 11.3) a.u.; $CI_{95\%diff} = 0.35$ (−0.77 to 1.46); $p = 1.00$], as observed in Figure 2b.

12×100-m

RPE

We observed an effect of condition ($X^2_{(3,63)} = 54.57$ $p < 0.001$) and distance ($X^2_{(1,63)} = 786.0$ $p < 0.001$), but no interaction effect ($X^2_{(3,63)} = 1.65$ $p = 0.645$) was found (Figure 3a). MF condition presented increased values for RPE [MF = 13.9 (13.7 to 14.1) a.u.; CON = 12.4 (12.0 to 12.8) a.u.; $CI_{95\%diff} = 1.49$ (1.1 to 1.9); $p < 0.001$].

Heart rate

We observed no condition ($X^2_{(1,16)} = 2.03$ $p = 0.154$) or interaction ($X^2_{(3,54)} = 0.353$ $p = 0.950$) effects. Only a distance effect ($X^2_{(1,54)} = 2608.45$ $p < 0.001$) was observed (Figure 3b).

TABLE 1 Characteristics of the participants.

	Men (6) Mean ± SD	Women (4) Mean ± SD
FINA Points	696 ± 47	716 ± 98
Age (years)	20.6 ± 3.1	21.5 ± 3.8
Height (cm)	184.3 ± 6.2	177.7 ± 7.5
Weight (kg)	81.5 ± 9.2	76.7 ± 7.8
BMI (kg.m^{-2})	23.9 ± 1.8	24.2 ± 1.3

FINA = Fédération Internationale de Natation; BMI = body mass index.

Lactate

We observed no condition ($X^2_{(1,9)} = 0.001$ $p = 0.974$) or interaction ($X^2_{(3,63)} = 1.07$ $p = 0.784$) effects, only a main effect of distance ($X^2_{(3,63)} = 1178.48$ $p < 0.001$), as seen in Figure 3c.

400-m

Performance

We observed a condition effect ($X^2_{(1,9)} = 117.14$ $p < 0.001$). The participants performed better in the CON than in the MF [CON = 277.0 (270.0 to 283.0) s; MF = 288.0 (281.0 to 294.0) s; $CI_{95\%diff} = -10.89$ (−12.86 to −8.92); p < 0.001] condition (Figure 4a).

RPE

We observed condition ($X^2_{(1,27)} = 8.56$ $p = 0.003$), time ($X^2_{(1,27)} = 810.2$ $p < 0.001$), and interaction effects ($X^2_{(1,27)} = 48.29$ $p < 0.001$). Participants in the MF condition presented increased RPE values in the pre-measurements [CON = 8.56 (8.12 to 9.00) a.u.; MF = 10.45 (9.97 to 10.93) a.u.; $CI_{95\%diff} = -9.68$ (−10.32 to −9.03); $p = 0.001$]. RPE increased from pre- to post-measurements for the CON [PRE = 8.56 (8.12 to 9.00) a.u.; POST = 18.24 (17.48 to 18.99) a.u.; $CI_{95\%diff} = -9.68$ (−10.32 to −9.03); p = 0.001] and MF [PRE = 10.45 (9.97 to 10.93) a.u.; POST = 18.54 (17.95 to 19.22) a.u.; $CI_{95\%diff} = -8.08$ (−8.74 to −7.42); p = 0.001] conditions. For the post-measurements, the conditions presented similar values [CON = 18.24 (17.48 to 18.99) a.u.; MF = 18.54 (17.95 to 19.22) a.u.; $CI_{95\%diff} = -0.30$ (−1.10 to 0.50); $p = 0.465$] (Figure 4b).

Heart rate

We observed no condition ($X^2_{(1,18)} = 1.16$ $p = 0.281$) or interaction ($X^2_{(1,18)} = 0.422$ $p = 0.516$) effects, only a time effect was observed ($X^2_{(1,9)} = 473.95$ $p = 0.001$) (Figure 4c).

Lactate

We observed condition ($X^2_{(1,18)} = 20.2$ $p = 0.001$), time ($X^2_{(1,9)} = 70.5$ $p = 0.001$), and interaction effects ($X^2_{(1,18)} = 36.2$ $p = 0.001$). La increased from pre- to post-measurements for the CON [PRE = 3.32 (2.40 to 4.23) mmol/L; POST = 10.24 (9.16 to 11.32) mmol/L; $CI_{95\%diff} = -7.01$ (−8.52 to −5.51); $p = 0.001$] and MF [PRE = 3.15 (2.41 to 3.90) mmol/L; POST = 9.02 (7.93 to 10.10) mmol/L; $CI_{95\%diff} = -6.92$ (−8.42 to −5.41); $p < 0.001$]. Additionally, post-measurements were different between conditions [CON = 10.24 (9.16 to 11.32) mmol/L; MF = 9.02 (7.93 to 10.10) mmol/L; $CI_{95\%diff} = 1.22$ (0.81 to 1.63); $p < 0.001$] (Figure 4d).

Discussion

We aimed to analyze the effects of mental fatigue on the perceptual and physiological responses to constant-speed swimming and 400-m front-crawl performance. We hypothesize that for the constant-speed test, only the perception of effort will display higher values in the mental fatigue condition with no major cardiovascular and metabolic alterations. A significantly higher RPE during the 12 × 100 m constant-speed test without significant HR and La alterations confirmed this hypothesis. The experiment also confirmed our hypothesis of reduced 400-m front-crawl performance in mentally fatigued swimmers.

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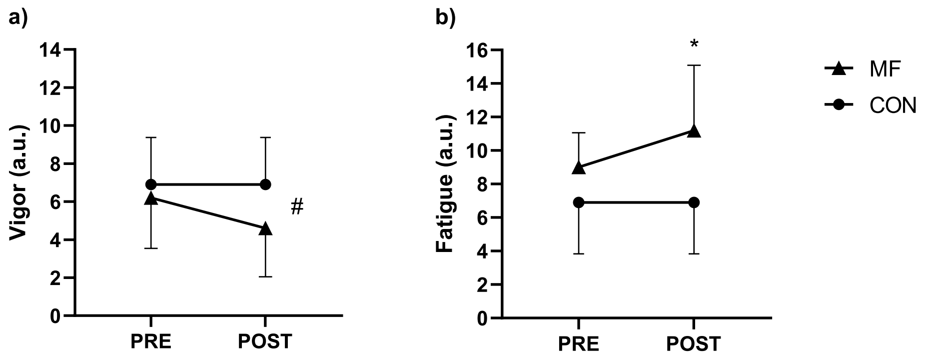

FIGURE 2
Manipulation check (*n* = 10). Mean and standard deviation of vigor **(a)** and fatigue **(b)**. Generalized Mixed Models, condition (2) × (2) time. * = different from control; # = condition effect.

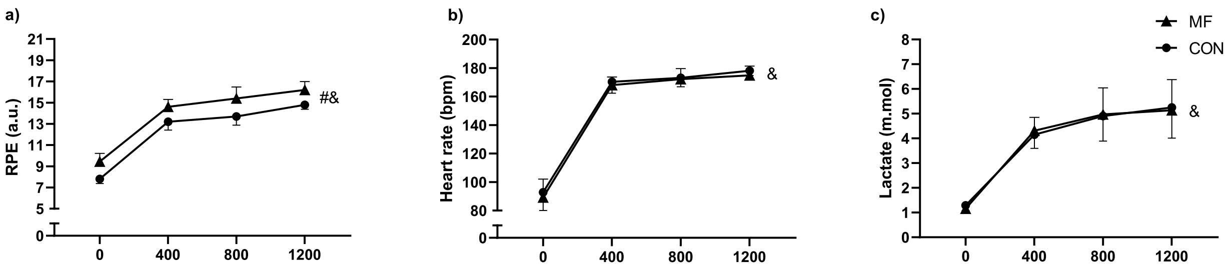

FIGURE 3
12 × 100-m test. Mean and standard deviation of RPE **(a)**, heart rate **(b)**, and lactate **(c)**. Generalized Mixed Models, condition (2) × (4) distance. RPE = rating of perceived exertion. * = different from control; # = condition effect; & = time effect.

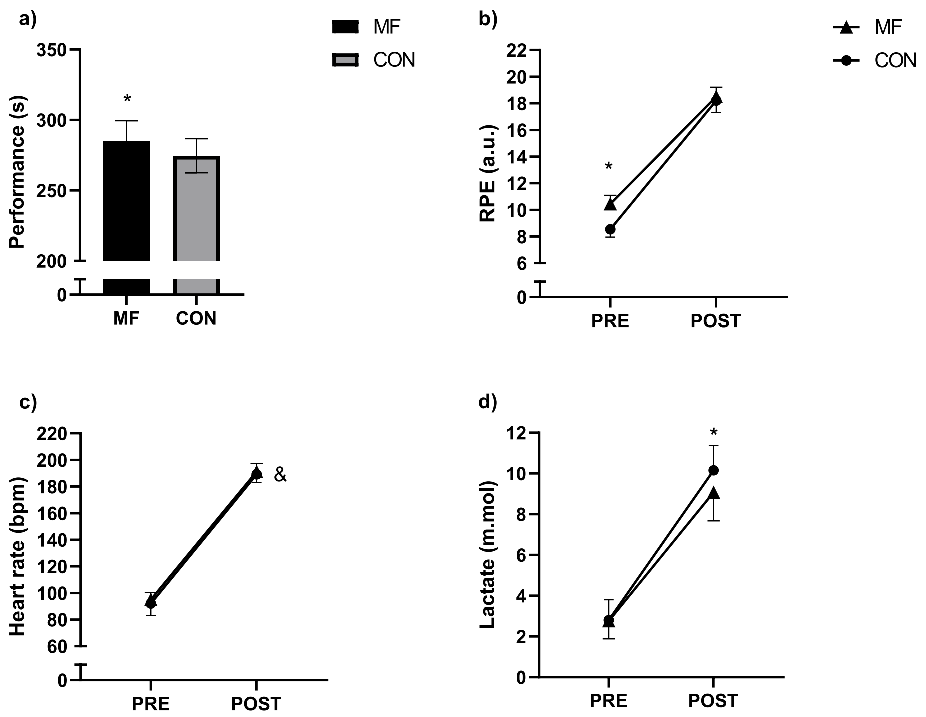

FIGURE 4
400-m test. Mean and standard deviation of performance **(a)**, RPE **(b)**, heart rate **(c)**, and lactate **(d)**. Generalized Mixed Models, condition (2) for **(a)** and condition (2) × (2) time for **(b,c)**. RPE = rating of perceived exertion; * = different from control; & = time effect.

In the 400-m test, mentally fatigued participants showed a mean performance reduction of 10 s (3.9%), aligning with findings from similar studies (Fortes et al., 2020; Penna et al., 2018). Penna et al. (2018) observed that following a 30-min Stroop task, young athletes reduced their 1,500-m freestyle performance by 1.2%, whereas in our study, a 3.9% was observed. Our study's more substantial negative effect might be related to a longer intervention (i.e., 90-min AX-CPT) as the literature suggests that more experienced athletes are less susceptible to the effects of mental fatigue (Martin et al., 2016). Studies should be conducted to clarify this point in the literature. Fortes et al. (2020) also found similar results for the freestyle 200-m, with a difference of approximately 2.0% between conditions. It is important to note that the differences between the first and third place in the 2024 Olympics for the men's 200, 400, and 1,500-m were 0.04, 0.2, and 0.6%, respectively (FINA, 2024).[2]

For the perceptual and physiological variables in the 400-m, only the lactate presented diverse results compared to literature. The participants in the mental fatigue condition began the test with a higher-than-normal perception of effort, which explains the reduced performance seen in previous studies (de Lima-Junior et al., 2024; Marcora et al., 1985; Pageaux et al., 2015). In mental fatigue studies, the physiological variables usually remain similar in the mental fatigue and control conditions (Marcora et al., 1985; Smith et al., 2016). However, we observed an increase in lactate levels for the control condition. It might be explained by the fact that participants in the control condition could develop more propulsion efficiency during the race due to technical aspects and lower perception of effort. HR (190 bpm), RPE (Russell et al., 2019) and La (11 mmol) at the end of the 400 m test suggest that participants produced a maximal effort during the test. The lower La at exhaustion in the MF condition can be explained by the lower speed produced during the test. The results were as expected in the constant speed 12×100-m test, in which the pacing was controlled during the whole test. Mental fatigue increased perception of effort despite no major cardiovascular and metabolic changes.

Although we consider our findings essential and innovative, some limitations must be mentioned. Our number of participants is small, reducing our generalizability and the possibility of stratifying analyses by sex. Furthermore, a small sample size reduces statistical power for small effects and increases the likelihood of observing large random effects due to higher sampling variability. Therefore, our results should be considered with caution. Nonetheless, our participants are national and international level athletes, which makes the number of ten participants substantial. Also, finding a significant number of high-level athletes who are specialists in a specific swimming technique different from the freestyle is demanding. Our study lacks biomechanical measurements such as stroke rate, stroke length, and propulsive efficiency. This could add interesting information about why 400-m front-crawl performance is reduced in mentally fatigued swimmers.

From a practical point of view, our study suggests that prolonged cognitive effort should be avoided before and between races. A state of mental fatigue should also be avoided before training sessions in which the coach wants to achieve high intensity and volume. However, recent studies suggest that combining physical training with demanding cognitive tasks (Brain Endurance Training, BET) may improve endurance performance (Marcora et al., 2015). Future research should investigate the effects of BET in swimmers. Furthermore, we should investigate the central effects of physical and mental fatigue and its effects on biomechanical and peripheral measurements in order to better understand and avoid performance impairments.

In conclusion, the present data confirms previous findings that mental fatigue impairs the performance of swimmers and suggest that such impairment is caused by an increase in perception of effort rather than significant cardiovascular and metabolic alterations.

2 https://www.worldaquatics.com/

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 University of Kent Research Ethics and Governance. 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

DL-J: Data curation, Formal Analysis, Project administration, Visualization, Writing – original draft, Writing – review & editing, Investigation. GC: Conceptualization, Data curation, Investigation, Writing – original draft, Writing – review & editing. MC: Conceptualization, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. LF: Data curation, Writing – original draft, Writing – review & editing. SM: Conceptualization, Data curation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing.

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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.

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References

Amann, M., and Dempsey, J. A. (2008). Locomotor muscle fatigue modifies central motor drive in healthy humans and imposes a limitation to exercise performance. *J. Physiol.* 586, 161–173. doi: 10.1113/jphysiol.2007.141838

Bishop, D., Jenkins, D. G., and Mackinnon, L. T. (1998). The relationship between plasma lactate parameters, Wpeak and 1-h cycling performance in women. *Med. Sci. Sports Exerc.* 30, 1270–1275. doi: 10.1097/00005768-199808000-00014

Buoite Stella, A., Cargnel, A., Raffini, A., Mazzari, L., Martini, M., Ajčević, M., et al. (2024). Shoulder Tensiomyography and isometric strength in swimmers before and after a fatiguing protocol. *J. Athl. Train.* 59, 738–744. doi: 10.4085/1062-6050-0265.23

Cutsem, J. V., and Marcora, S. (2021). "The effects of mental fatigue on sport performance: an update" in Motivation and self-regulation in sport and exercise (London: Routledge).

de Lima-Junior, D., Gantois, P., Nakamura, F. Y., Marcora, S. M., Batista, G. R., Bartolomei, S., et al. (2024). Mental fatigue impairs the number of repetitions to muscular failure in the half back-squat exercise for low- and mid- but not high-intensity resistance exercise. *Eur. J. Sport Sci.* 24, 395–404. doi: 10.1002/ejsc.12029

Fortes, L. S., Nakamura, F. Y., Lima-Junior, D., Ferreira, M. E. C., and Fonseca, F. S. (2020). Does social media use on smartphones influence endurance, power, and swimming performance in high-level swimmers? *Res. Q. Exerc. Sport* 93, 120–129. doi: 10.1080/02701367.2020.1810848

Habay, J., Van Cutsem, J., Verschueren, J., De Bock, S., Proost, M., De Wachter, J., et al. (2021). Mental fatigue and sport-specific psychomotor performance: a systematic review. *Sports Med.* 51, 1527–1548. doi: 10.1007/s40279-021-01429-6

Liang, K.-Y., and Zeger, S. L. (1986). Longitudinal data analysis using generalized linear models. *Biometrika* 73, 13–22. doi: 10.1093/biomet/73.1.13

Marcora, S. M., Staiano, W., and Manning, V. (1985). Mental fatigue impairs physical performance in humans. *J. Appl. Physiol.* 106, 857–864. doi: 10.1152/japplphysiol.91324.2008

Marcora, S. M., Staiano, W., and Merlini, M. (2015). A randomized controlled trial of brain endurance training (BET) to reduce fatigue during endurance exercise: 754 board #150 may 27, 3 30 PM - 5 00 PM. *Med. Sci. Sports Exerc.* 47:198. doi: 10.1016/j.jsams.2023.05.008

Martin, K., Staiano, W., Menaspà, P., Hennessey, T., Marcora, S., Keegan, R., et al. (2016). Superior inhibitory control and resistance to mental fatigue in professional road cyclists. *PLoS One* 11:e0159907. doi: 10.1371/journal.pone.0159907

Mellalieu, S., Jones, C., Wagstaff, C., Kemp, S., and Cross, M. J. (2021). Measuring psychological load in sport. *Int. J. Sports Med.* 42, 782–788. doi: 10.1055/a-1446-9642

Pageaux, B., and Lepers, R. (2016). Fatigue induced by physical and mental exertion increases perception of effort and impairs subsequent endurance performance. *Front. Physiol.* 7:587. doi: 10.3389/fphys.2016.00587

Pageaux, B., Marcora, S. M., Rozand, V., and Lepers, R. (2015). Mental fatigue induced by prolonged self-regulation does not exacerbate central fatigue during subsequent whole-body endurance exercise. *Front. Hum. Neurosci.* 9:67. doi: 10.3389/fnhum.2015.00067

Penna, E. M., Filho, E., Wanner, S. P., Quinan, G. R., Mendes, T. T., Smith, M. R., et al. (2018). Mental fatigue impairs physical performance in young swimmers. *Pediatr. Exerc. Sci.* 30, 208–215.

Pyne, D. B. (2001). Monitoring the lactate threshold in world-ranked swimmers. *Med. Sci. Sports Exerc.* 33, 291–297.

Quagliarotti, C., Coloretti, V., Dello Stritto, E., Cuccurullo, S., Acalai, J., Lepers, R., et al. (2023). Does smartphone use affect a subsequent swimming training session? Preliminary Results in Amateur Triathletes. *Sensors* 23:5837. doi: 10.3390/s23135837

Russell, S., Jenkins, D., Steven, R., Halson, Shona, L., and Kelly, V. (2019). What is mental fatigue in elite sport? Perceptions from athletes and staff. *Eur. J. Sport Sci.* 19, 1367–1376. doi: 10.1080/17461391.2019.1618397

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

Terry, P. C., Lane, A. M., and Fogarty, G. J. (2003). Construct validity of the profile of mood states — adolescents for use with adults. *Psychol. Sport Exerc.* 4, 125–139. doi: 10.1016/S1469-0292(01)00035-8

Walsh, V. (2014). Is sport the brain's biggest challenge? *Curr. Biol.* 24, R859–R860. doi: 10.1016/j.cub.2014.08.003

Yoma, M., Herrington, L., Mackenzie, T. A., and Almond, T. A. (2020). Training intensity and shoulder musculoskeletal physical quality responses in competitive swimmers. *J. Athl. Train.* 56, 54–63. doi: 10.4085/1062-6050-0357.19

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Understanding of mental fatigue in elite fencing sports: perspectives from Chinese national level fencers

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Introduction: Recent studies have documented the presence, fluctuation, and persistence of mental fatigue (MF) across various elite sports. It appears that open-skilled competitive contexts tend to impose greater mental demands, leading to higher levels of MF. Fencing, as an open-skilled combat sport, requires perceptual-cognitive skills and mental resources allocation for an optimal performance. However, it is underrepresented in the MF research domain.

Methods: This study employed a cross-sectional design using an online survey to capture Tier 3–5 Chinese fencers' perceptions of MF and their general understanding of the contributors that may induce MF in fencing. Descriptive reports, thematic analysis, comparisons of retrospective MF perceptions (MVAS) and different contributors to MF inducement in training and competition were conducted.

Results: The results highlight a contextual difference of MF (training vs. competition), and the contributions of timing-related decision-making moments and execution of offensive actions to the MF inducement in fencing. Furthermore, MF was perceived higher in the direct elimination stage competition than in the pool stage (MVAS: 57.6 ± 21.0 vs. 49.2 ± 21.7 AU). Individuals' health conditions and competition-oriented elements were rated as synergistic factors of MF perception, while external commitments were rated lower.

Discussion: These findings emphasize the presence of MF in fencers and encourage researchers and practitioners to assess and deliberately manage MF. Future studies should involve longitudinal, multifactor observations on diverse fencers and contexts to validate current findings, with a focus on specific in-match scenarios to enhance the representativeness and inform targeted training and management strategies for MF in fencing.

KEYWORDS
cognitive fatigue, qualitative study, combat sports, epee, foil, sabre

1 Introduction

Mental fatigue is a psychobiological state induced by prolonged cognitive activity. It is characterized by a subjective feeling of tiredness, reduced cognitive capacity, and altered brain activation (Boksem and Tops, 2008). Laboratory-based studies suggest that mental fatigue impacts subsequent physical performance, psychomotor performance including decision-making ability, reaction speed, and accuracy, as well as key aspects of technical and tactical performance (Habay et al., 2021). Possible mechanisms underlying these negative mental fatigue effects are linked to complex neural mechanisms, motivation, and resource depletion (e.g., brain phosphocreatine) (Habay et al., 2021). Over the past decade, mental fatigue has received increased significant attention, especially in the context of elite and professional sports (Roelands et al., 2021). Researchers have increasingly utilized accessible tools, such as self-reported scales and questionnaires, to monitor mental fatigue longitudinally in elite athletes. Studies have documented the presence, fluctuation, and temporal nature of mental fatigue across various sports contexts, including team sports [i.e., football (Abbott et al., 2020; Thompson et al., 2021; Díaz-García et al., 2023)], netball (Russell et al., 2022a,b), rugby (Mariano et al., 2023), beach volleyball (Da Costa et al., 2023), padel (Diaz-Garcia et al., 2021), and orienteering (Lam et al., 2023). Despite the accumulating body of research, the variations, specificity, and nature of differing applied contexts make it challenging to draw broader conclusions to generalize across sports. However, open-skilled competitive contexts, which require rapid responses to unpredictable and dynamic environments in competitions, tend to impose greater mental demands and thus result in higher levels of mental fatigue compared to some closed-skilled sports (Coyne et al., 2021).

Fencing is an open-skilled combat sport that encompasses three main disciplines, categorized by the type of sword: epee, foil, and sabre (Roi and Bianchedi, 2008). Regardless of fencing gender, the average duration of a single combat bout is 17.9 ± 3.1 s for epee, 5.8 ± 2.5 s for foil, and 1.7 ± 0.4 s for sabre, with corresponding work-to-rest ratios of 1:0.9, 1:2.6, and 1:9.2, respectively (Tarragó et al., 2023). Typically, an international match day (lasting between 9 and 11 h) for a single fencing discipline includes a preliminary round (i.e., pool stage, lasting up to 3 min or first to five touches) and direct elimination rounds (up to 9 min each or first to 15 touches), with a total effective combat time ranging from 17 to 48 min (Roi and Bianchedi, 2008). The high intermittency and specific movement patterns inherent in fencing reduce anaerobic contributions during a match (Yang et al., 2022), leading to non-maximal physiological demands (Roi and Bianchedi, 2008) and relatively minor physical fatigue, as indicated by physiological (Varesco et al., 2023) and biochemical measures (Turner et al., 2017).

Despite its moderate physical demands, fencing is a highly technical and tactical sport that imposes significant cognitive load (Varesco et al., 2023). Continuous attention and rapid information processing are essential for analyzing and selecting visual cues from the opponent during fencing combat (Varesco et al., 2023; Varesco et al., 2024). Combined with making precise decisions, fencers must execute fast reactions and superior response inhibition, requiring excellent coordination and body control to achieve both speed and accuracy in their most appropriate movements within extremely short timeframes (Roi and Bianchedi, 2008; Gutiérrez-Davila et al., 2019). Furthermore, emotional regulation is highly demanded during fencing competitions due to frequent interruptions and switching between winning and losing situations throughout the stressful bouts (Doron and Martinent, 2021). It remains unclear whether the prolonged, yet intermittent, interactions involving multiple perceptual, motor, and cognitive demands in fencing (Bagot et al., 2023) lead to mental fatigue, and how this might impact specific performance capacity. However, given findings in prior sports demonstrating impacts on performance aspects important to fencing, i.e., tactical errors, slower reaction, reduced attack accuracy (Habay et al., 2021), it is reasonable to propose a potential impact. Furthermore, evidence supporting impaired decision-making ability previously found in boxing athletes following artificially induced mental fatigue (Fortes et al., 2023), demonstrates relevance to sports of a similar structure.

Primary evidence suggests that the gradual subjective manifestation of fatigue in simulated fencing competitions is linked to a significantly increased mental demand (Varesco et al., 2023). Accordingly, fatigue in real-world fencing may also predominantly result from the mental demand component. However, this has not been established yet. Given the relatively unexplored nature of this topic, especially the scarcity of quantitative mental fatigue research in fencing sports, qualitative methods provide a valuable approach to gather initial insights and establish foundational knowledge (Harper and McCunn, 2017). These qualitative findings were selected to provide a strong base to inform and guide the relevance and ecologically validity of future studies. Therefore, the purpose of this study was to design and implement a bespoke online survey for national fencing-level practitioners, aiming to investigate fencers' perceptions of mental fatigue and their general understanding of the factors that may induce mental fatigue in fencing.

2 Methods

2.1 Study design

This study employed a cross-sectional design using an anonymous online survey. Given the survey targeted a specific fencing community, it was initially developed by the primary researchers in English but was administered in the participants' native language, to ensure clarity and accurate expression of intent. A 10-person expert panel assisted in piloting, and provided feedback from which the survey was refined and adjusted to ensure appropriate length, structure, and clarity of questioning, prior to the final distribution. Only participants who voluntarily agreed to participate and provided informed consent were included. The project was conducted in accordance with the principles outlined in the Declaration of Helsinki and received ethical approval from Scientific Research Ethics Committee of Shanghai University of Sport (No. 102772023RT058).

2.2 Participants and inclusion criteria

The study used purposeful sampling to provide opportunity to include Chinese national or international level [i.e., Tier 3–5 (McKay et al., 2021)] fencing athletes across nationwide training centers and camps. Participants consisted of active fencers, as well as retired fencers with equivalent athletic levels who concurrently held team coaching, assistant, or management roles. Referees were excluded from the analysis. Eligible participants were required to be over 18 years old and in good physical and mental health determined by the absence of current injury and medication. Participants were encouraged to respond the survey individually in a neutral emotional and cognitive state.

2.3 Data collection

The survey was administrated via the Chinese Sojump online platform[1] and was accessible on participants personal electronic devices through a sharable digital link. For inclusion of response in the data set, respondents' informed consent and completion of all survey questions were required. The conditional formatting applied in the online system prohibited next-page navigation, skipping questions, or background reading to encourage quality completion that was representative of the participants' current perception. Completion time and platform identifier code were automatically recorded for validity check. The online link to the survey was distributed by an expert fencing panel, Chinese Fencing Association, and Fencing Academy of China.

2.4 Survey design, pilot, and finalization

Given the exploratory nature of the bespoke, cross-sectional survey, and the targeted high-level fencer's distinct feelings might fluctuate over time due to the changing environment and state, only content validity was considered (Anyadike-Danes et al., 2023). The theoretical framework for defining the workload factors contributing to the mental fatigue inducement in fencing was grounded on the concepts of internal/external load and fatigue (Halson, 2014). The decomposition of crucial moments in fencing bouts, considered as potential contributors to mental fatigue from a temporal perspective, was supported by time-motion analyses in foil, sabre (Aquili et al., 2013), and epee (Yang et al., 2022). The motion schemes of fencing experts also provided important reference.

The three researchers (CB, SR, BR), with both mental fatigue and sports domain expertise, designed the general survey constructs and logic in English. A bilingual researcher (CB) then translated the survey into Chinese on the platform and assembled an expert panel (n = 10) for two rounds of piloting and refinement. The panel included two coaches, one administrator, and three active fencers from the national fencing academy with undergraduate or above education level, one mentor from collegiate fencing teaching group, one performance director of the national fencing team, one leading lecturer of the national Foil coaching courses, and one sports science professor. They first reviewed and modified the draft independently, checked the clarity and the intention of every item, and evaluated content including fencing specificity. The pilot feedback was compiled and incorporated into a revised version of the survey. To ensure the revisions provided the desired clarity, an online meeting was held between pilot members and the lead author to resolve differing suggestions and reach unanimous approval through a public review and feedback process. This version was then finalized and activated for distribution.

2.5 Survey construction and details

The survey was organized into five sections, presented across five pages: an initial page for informed consent, a page outlining the background of the mental fatigue concept in sports, and three pages containing 17 questions. The original survey has been uploaded as a Supplementary Material. The response formats included single-select, multi-select, one open-ended answer, and visual analog scale (VAS) sliding matrixes. The order of options within the multiple-select and the VAS matrix were presented in a randomized manner, as allocated by the platform's conditional logic. The survey structure covered several key areas: Basic information (identity, fencing experience); Perceptions of mental fatigue (general attitude toward mental fatigue, retrospective self-reported perception of mental fatigue (MVAS) in different fencing contexts, descriptions of mental fatigue in fencing, and synergistic influence factors on mental fatigue); and Understanding the mental fatigue inducement process and contributors (examining the impact of five general workload factors - physical, technical, tactical, psychological, and environmental loads in the training and competition contexts; and six critical combat moments - posture preparation, step movement, timing decision-making, attack, defense, and riposte execution in fencing bouts). Participants responded to the multiple contributors via presentation of a VAS matrix, with each rated by sliding each individual VAS to indicate its relative contribution.

2.6 Data analysis

All original answers were exported from the platform in an Excel (Version 16.71, Microsoft, Redmond, U.S.) file. The completion duration and unique participant identifier was screened for potential duplication. All complete responses were included in the data corpus for analysis. Descriptive analyses were conducted in Excel. The mean with standard deviation (± SD) was presented for quantitative variables, while the response percentage (%) among all valid responses was reported for single- or multi-select items. The median value (i.e., 50 AU) of the digital VAS full scale range was defined as the cut-off for moderate-level fatigue perception (Nordin et al., 2016) when interpreting the retrospective MVAS results.

Further analysis was conducted in SPSS (Version 25, IBM, Chicago, U.S.). The Kolmogorov–Smirnov normality test was run to check and confirmed normal distributions for the MVAS outcomes. The MVAS were compared across contexts by paired t-test. Cohen's d effect size was calculated in case of significant difference between two contexts, with conventional thresholds applied: 0.20 (small), 0.50 (medium), and 0.80 (large). The perceived contribution data from one VAS matrix, which included five different workload factors during training, five workload factors during competition, and six combat moments in fencing bouts, were normalized to a total of 100%. In cases where some contribution rates followed a non-normal distribution, the Wilcoxon signed-rank tests were applied to compare all contributors within the matrix and between the different contexts (i.e., training and competition). The significance level was set at $p < 0.05$ (two-tailed).

1 www.sojump.com

NVivo (Version 12, Lumivero, Denver, U.S.) software was used to code the original texts generated from the open-ended descriptions of mental fatigue in fencing. The software was also utilized to analyze and connect the codes to establish higher themes, define and name themes, and interpret the answers, which followed the thematic analysis guidelines (Braun and Clarke, 2006). Due to the bilingual context, the primary codes were extracted in Chinese for better understanding and more accurate translation by the lead researcher (CB). Following subsequent translation to English the summarization and construction of concepts, cross-checking of the translated codes, and allocation to themes, was undertaken by two researchers independently (CB and SR). Following this, the obtained outcomes were translated back into Chinese for a final inspection of alignment with the original responses in the participants' native language. The back-and-forth translations process followed Weiler et al. (2024) in the bilingual environment.

3 Results

The online link to the survey remained open for a total of eight weeks, across two periods; mid-August to mid-September 2023, and the October 2023. The data collection period deliberately avoided the potential interference of the major international fencing event, the Asian Games. The survey received a total of 102 responses, of which 92 valid responses were included in the final analysis. Seven practitioners who only identified as fencing referees or staff without indicating systematic fencing training experience were excluded on the basis of lack of fencing-specific expertise. Another three respondents who chose "not at all" in the ability to differentiate mental fatigue from physical fatigue were excluded to minimize data that was not representative of perceptions and opinions of those who indicated to hold insight into the concept of mental fatigue. The average time to complete the survey was 7.3 ± 4.8 min per valid respondent.

3.1 Participant demographics

Responders were female (37.0%) and male (63.0%) adult fencing athletes or team practitioners with the Tier 3–5 profiles across all three disciplines. As shown in the Table 1, the majority were 18–25-year-old (91.3%), Tier 3 (60.9%) active fencers (76.1%). Thirty-four had Tier 4 profiles, and two belonged to Tier 5.

3.2 Perception of mental fatigue in fencing

Regarding the attitudes toward the mental fatigue, more than half (57.6%) of fencers indicated difficulty in consistently distinguishing between mental and physical fatigue after fencing practice. In addition to the provided mental fatigue definition, developed from perceptions across other sports, 62 respondents contributed additional phrases to describe mental fatigue in fencing. Twenty-three (37.1%) respondents directly stated experience of the above-normal fatigue. They highlighted that mental fatigue happened in the match-related contexts. The mental fatigue in fencing was generally associated with negative emotional, psychomotor, and bodily responses (see Table 2). It was also perceived to cause subsequent sleep disturbance.

Based on previous fencing experience, participants recalled and reported the MVAS with 47.6 ± 18.7 AU in a typical comprehensive training session, with 49.2 ± 21.7 AU in the pool stage on an official match day with equivalent opponents, while the perception rated 57.6 ± 21.0 AU in the direct elimination stage was significantly higher than in the pool stage ($t = 4.14$, Cohen's d = 0.39, $p < 0.001$). All fencers acknowledged the negative effects of mental fatigue on performance and health. They identified sleep quality (78.3%), match environment (50.0%), preparation duration (43.5%), diet (41.3%), and emotion (38.0%) might increase mental fatigue alongside fencing practice, followed by other factors such as interpersonal relationships (31.5%), non-fencing work (29.4%), academic requirements (23.9%), family ties (21.7%), transportation (12.0%), and media (6.5%). A high number of participants (84.8%) indicated that the integration of mental fatigue targeted training could also induce positive effects on fencing performance.

3.3 Contributors to mental fatigue inducement in fencing

From the perspective of different workload factors that might contribute to the overall mental fatigue after fencing activities, significant differences between training and competition contexts were only observed in the tactical factor (see Figure 1A, 20.0% in training vs. 21.8% in competition, $p = 0.01$), while other factors showed no significant changes (physical, $p = 0.07$; technical, $p = 0.77$; psychological, $p = 0.84$; environmental, $p = 0.54$).

From the perspective of the combat execution moments of the fencing bouts in Figure 1B, respondents assessed the contributions of each moment in inducing the overall mental fatigue, with rates indicating that the accumulative moments of timing decision-making and attack execution (21.6% vs. 19.6%, $p = 0.22$) have the greatest contribution.

4 Discussion

The results derived from this cross-sectional survey provided insights into the subjective experience of mental fatigue and an understanding of its potential inducement process among (inter)

TABLE 1 Demographic information of age, gender, fencing identity, fencing discipline, athlete tier, and years of experience in athletes.

Age/years		Gender		Identity		Discipline		Athletic level		Experience/years	
18–25	91.3%	Female	37.0%	Active	76.1%	Epee	33.7%	Tier 3	60.9%	Career	10.0 ± 4.6
26–30	3.3%	Male	63.0%	Retired	23.9%	Foil	34.8%	Tier 4	36.9%	Provincial	6.8 ± 5.4
31–40	3.3%	Others	0.0%	Coach	12.0%	Sabre	28.2%	Tier 5	2.2%	National	2.2 ± 2.8
41–50	2.2%			Others	4.3%	Undefined	3.3%			International	1.2 ± 2.2

Presents as percentage of total participants and fencing experience presents in mean ± standard deviation.

TABLE 2 Thematic analysis presenting participants' perceptions of feelings associated with mental fatigue in fencing.

Theme	Main code	Frequency (n = 62)	Percentage
Emphasis the term	Very tired	23	37.1%
Match-related context	During match	19	30.6%
	Unsatisfied results	12	19.4%
	After match	7	11.3%
Emotional response	Disgusted	16	25.8%
	Annoyed	5	8.1%
	Stressful	5	8.1%
	Anxious	4	6.5%
Psychomotor response	Disengaging thought	13	21.0%
	Blank mind	9	14.5%
	Recalling	6	9.7%
	Decreased attention	4	6.5%
	Slow reaction	3	4.8%
Somatic response	Headache	16	25.8%
	Powerless body	6	9.7%
Sleep disturbance	Drowsiness	6	9.7%
	Insomnia	3	4.8%

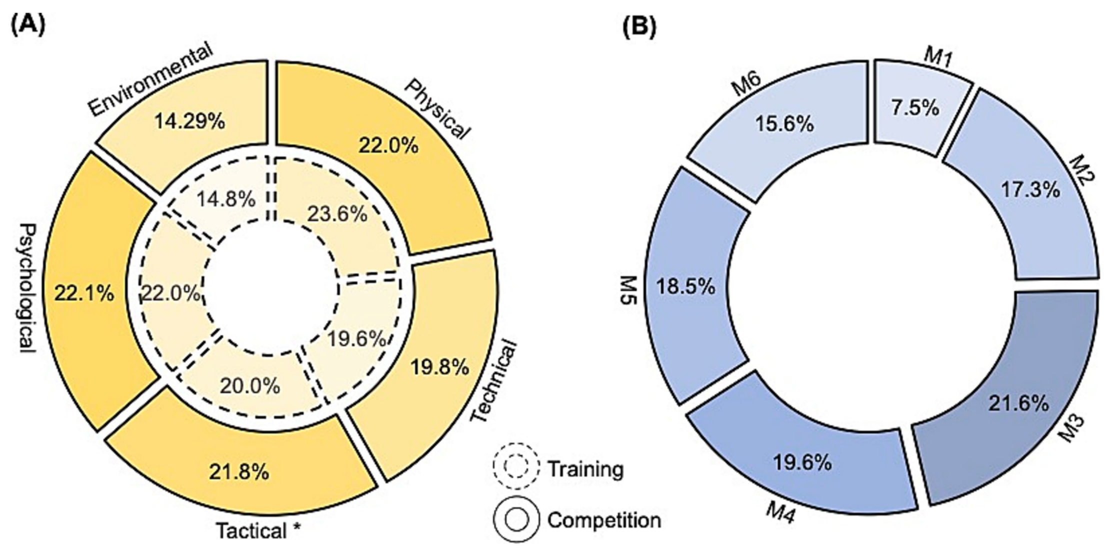

FIGURE 1
Perceived contributors to the overall mental fatigue inducement process. **(A)** Contributions from five general workloads; the inner circle means in the training context, and the outer circle means in the competition context. **(B)** Contributions from six general fencing combat moments in fencing bouts; M1, posture preparation; M2, step movement; M3, timing decision-making; M4, attack; M5, defense; M6, riposte; *, significant differences of contributions for competition, compared with the contribution in the training context.

national level fencers. The survey highlighted an elevated mental fatigue perception on match days due to significantly higher tactical load compared to training days. The above-moderate level of MVAS was only retrospectively reported by fencers when the competition context switched from the pool stage to the direct elimination stage. The accumulative timing decision-making process and offensive moments were reported to contribute most to the mental fatigue inducement.

4.1 Representativeness of the respondents

Respondents demonstrated high proficiency with national or international experience, representing Tiers 3–5 (McKay et al., 2021) of the sport. The active junior (18–20 years) and senior (> 20 years) fencers aligned with the relatively young age focus in fencing research (Harmer, 2019). The female/male distribution of respondents was consistent with another survey conducted on the

British fencing community, with a similar 40% being female (Morris et al., 2022). The relatively balanced distribution enhances the generalization of this survey's findings. Nevertheless, no evidence of discipline- and gender-specific differences was found by monitoring subjective fatigue and mental effort through simulated combats in elite fencing (Varesco et al., 2023). These findings supported analysis and interpretation of the survey from a unified perspective of the elite fencing population including current and recently retired athletes.

4.2 Perception of mental fatigue in fencing

4.2.1 General attitudes to mental fatigue

The findings indicate fencers have a nuanced perception of the concept of mental fatigue. More than half expressed uncertainty in distinguishing mental fatigue from physical fatigue following fencing practice. This aligns with previous research indicating that athletes and staff may find it "hard to decouple" mental and physical fatigue (Russell et al., 2019). This also aligns with the self-evaluated higher contribution of physical workloads to overall mental fatigue in training sessions. As fatigue is multifactorial in nature (Halson, 2014), it manifests as a dynamic event involving subjective, mental, behavioral, neural, and physiological processes that interact over time and across contexts (Tran et al., 2020).

The survey responses indicate that fencers recognized the negative effects of mental fatigue, yet, the community was also aware of the potential benefit of inducing mental fatigue in training. Indeed, it offers increased opportunities for learning, adaptation, management, and the development of tolerance and resilience (Russell et al., 2024). Long-term training adaptation could help more experienced athletes have greater resistance to mental fatigue and the potential negative effects on subsequent performance (Russell et al., 2019). The perception among fencers paves the way for practitioners to incorporate more cognitive training elements into physical practice and the overall training prescription, facilitating the potential application of sport-specific elements of brain endurance training (Roelands and Bogataj, 2024) in fencing sports to benefit the performance level.

4.2.2 Feelings associated with mental fatigue

Fencers expressed above-normal tiredness, negative alterations in emotional states and psychomotor functions when mentally fatigued. Consistent with the laboratory findings, the mental fatigue state has been proven to increase the perceived effort (Pageaux and Lepers, 2016). In certain cases, mental fatigue has been associated with changes in motivational states or negative feelings such as anxiety, frustration, and boredom, with the person experiencing aversion to continue performing tasks (Diaz-Garcia et al., 2021). An effort-reward imbalance may occur (Boksem and Tops, 2008) in mentally fatigued fencers, which stimulates the mental inhibition system to avoid disruption of normal homeostasis (Salihu et al., 2022). This protective mechanism drives thoughts of disengagement, discomfort, and reduces enthusiasm from fencing activities, which is consistent with other elite athlete's most frequently identified behavioral descriptors in mental fatigue (Russell et al., 2019).

4.2.3 Contextual differences in mental fatigue perception

The retrospectively self-reported MVAS data showed noticeable variations between the training and competitive contexts. In regular training sessions and the initial pool stage of the match day, the MVAS scores were rated lower compared to the context of direct eliminatory stage, where a nearly moderate level increase was observed. The high intermittency of fencing practice, characterized by the short duration of assaults within bouts, and recovery time settings between bouts and games, likely prevented the mental fatigue perception reaching a maximal level (Turner et al., 2017; Varesco et al., 2023). Meanwhile, the fencers' distinct feelings about mental fatigue in different contexts are supported by longitudinal evidence from other sports, a similar elevation of mental fatigue after successive eliminatory matches has been reported during the professional padel tournament (Diaz-Garcia et al., 2021). The mental fatigue also increased from the regular season to the playoffs in semi-professional soccer (Díaz-García et al., 2023), and during the pre-season training phase when the season approached (Russell et al., 2022b). On match days, where multiple matches or bouts of competition (such as tournament style play) occur, there appears to be an accumulation of mental fatigue (Varesco et al., 2023). This may also be attributed to match difficulties, with more tactical demands and psychological workloads as the match and tournament progress towards the finals (Roi and Bianchedi, 2008; Diaz-Garcia et al., 2021). These fencers recognized the presence of mental fatigue across training and competition, with the perception of mental fatigue tending to be elevated in the later stages of competition. The potential carry-over of mental fatigue from earlier matches and training schedules, needs further investigation during fencing competitions over a longer time frame.

4.2.4 Other factors perceived to relate to mental fatigue

Besides training and competition, other daily cognitive activities and well-being factors were also suggested to play a role in mental fatigue perception, aligning with prior research findings (Russell et al., 2019; Abbott et al., 2020). Fencers recognized that individuals' health factors (i.e., sleep, diet, and emotion) and competition-oriented elements (i.e., match environment and preparation) synergistically affected mental fatigue. Indeed, sleep has been previously found to have a strong correlation with mental fatigue among professional soccer players during an under-23 Premier League season (Abbott et al., 2020). Inadequate sleep and nutrition, as well as negative emotions, can lead to impairments in specific brain function related to the specific brain regions or networks and aspects of athletic performance, which in turn may negatively affect fencers' effort and fatigue perception (Mata et al., 2021).

Fencers less strongly perceived their external commitments such as managing relationships, extra work and education, family, transportation, and media to induce mental fatigue. It is contrary to other studies that primarily focused on team based sports (i.e., netball, football), where the athletes and staff recognized such external commitments as a higher order theme related to the presence of mental fatigue (Russell et al., 2019; Thompson et al., 2021). The differences in findings demonstrate that national-level fencing environment may provide unique stimulus. Commonly, elite fencers engage in more personalized drills at a closed-off training base, competition-oriented training and targeted fencing events occupy their entire careers, thus they may be arguably more prepared individually to manage mental fatigue. This structure differs from the majority of professional team sports which have continuous weekly home-away matches in seasons with frequent transportation, high media attention, and more intra-teamwork. Additionally, athletes' personality types and psychological profiles may differ in one-on-one combat sports. National Foil fencers' typical traits were profiled as independent and reserved (Roi and Bianchedi, 2008). Plausibly, elite fencers focus on themselves and associate the mental fatigue with a distinct, personal concern related to health and competition. These individual health factors (e.g., sleep, diet, emotional state), their relationships with mental fatigue post-fencing activities, and the interactions with fencer's daily routines, need to be explored in future studies.

4.3 Understanding fencing-specific contributors to mental fatigue inducement

This study introduced novel perspectives on the mental fatigue inducement process, comparing general workload factors and combat moments that fencers rated to contribute to overall perception of mental fatigue. Significantly higher tactical loads accounted for the elevated MVAS post-competition compared to post-training, indicated by retrospective self-reports. The accumulative execution of timing-related decision-making, particularly in attacks, was rated as the most effortful moment that induced mental fatigue during the match.

Fencing is inherently a more offensive activity, in which a single attack can be initiated and completed within a very short time, often requiring immediate and decisive actions (Aquili et al., 2013). Fencers must continuously adapt their tactical strategies, execute precise techniques rapidly, and manage psychological load under competitive pressure (Gutiérrez-Davila et al., 2019; Doron and Martinent, 2021). Although movement speed is important, a key ability is to recognize the best time for starting an attack in response to the opponent's actions (Roi and Bianchedi, 2008). This may explain the higher contribution of tactical loads to mental fatigue in the one-on-one competitive context. Adjustments to the tactical components of in-season training should be considered, along with the implementation of strategies to manage mental fatigue following intensive tactical sessions in the pre-competition period.

In fencing, cognitive skills such as visual–spatial attention, discrimination, and decision-making are essential to score (Varesco et al., 2024). Fencers perceived that the accumulative moments of timing decision-making contributed most to the mental fatigue inducement. Effective decision-making in fencing involves the allocation of cognitive resources to internal or external stimuli, the rapid analysis of the opponent's subtle cues from body language (e.g., arm and leg span), previous actions, distance, and sword information (Turner et al., 2017), predicting and selecting appropriate responses, all of which demand substantial mental loads (Varesco et al., 2023). Based on these findings, future studies could design and test representative mental fatigue-inducing tasks and scenario-based simulations for fencing-specific research and training practice with high ecological validity.

4.4 Strengths and limitations

The current survey showed practical value for future research and practice by capturing direct perceptions and understanding of the mental fatigue inducement from representative fencing athletes and practitioners. However, the cross-sectional and exploratory approach to the study limits the inferred causality between mental fatigue and fencing performance aspects. The participant group in this survey is representative of current and recently retired Chinese (inter)national-level fencing athletes, accordingly caution should be taken in extending or generalizing findings beyond this population.

4.5 Future directions for research and practice

This study forms a strong foundation for research and practice on mental fatigue in fencing sports. Future studies should include a diverse sample of fencers and incorporate long-term multifactor observations to validate and extend the current findings, for example by capturing real-time behavioral and neurophysiological data. Longitudinally tracking over different phases of training and matches could provide further evidence on the reported contextual difference and temporal/accumulative profiles of fencing-specific mental fatigue. Practitioners should place greater awareness on understanding the mental states of fencers, particularly emphasizing the role of individual health factors, pre-competition preparation quality, and the tactical component in training to mitigate mental fatigue and enhance performance. Additionally, to better understand the contributors to mental fatigue, it is important to examine how specific in-game scenarios, such as offensive situations and timing-related decision-making tasks in fencing bouts, impact performance when applied to deliberately induce mental fatigue. This will further support mental fatigue studies with greater ecological validity and will enhance mental fatigue-based training and management in practical settings.

5 Conclusion

This cross-sectional survey collected the mental fatigue perceptions and general understanding of the mental fatigue inducement process in fencing from an (inter)national athletes level perspective. It highlighted the contextual differences of mental fatigue (training vs. competition), and the contributions of timing decision-making and offensive moments to the mental fatigue inducement in fencing. Furthermore, mental fatigue was perceived higher when fencing context switched from the tournament pool stage to the direct elimination stage. Individuals' health conditions and competition-oriented elements were rated as the most significant synergistic factors in the perception of mental fatigue, while the external commitments were rated lower. These findings emphasize the presence of mental fatigue in fencers and encourage researchers and practitioners to effectively identify and deliberately manage mental fatigue.

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 Scientific Research Ethics Committee of Shanghai University of Sport (102772023RT058). 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

CB: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. SR: Conceptualization, Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing. KP: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. JH: Data curation, Formal analysis, Writing – original draft, Writing – review & editing. ŠB: Formal analysis, Visualization, Writing – original draft, Writing – review & editing. BR: Conceptualization, Supervision, Validation, Writing – original draft, Writing – review & editing.

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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 handling editor LDSF declared a past collaboration with the author BR.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. In the initial draft, minor grammatical refinements were assessed by Google Translate (May 2024). Final content remains fully human-authored and validated.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2025.1512326/full#supplementary-material

References

Abbott, W., Brownlee, T. E., Naughton, R. J., Clifford, T., Page, R., and Harper, L. D. (2020). Changes in perceptions of mental fatigue during a season in professional under-23 English premier league soccer players. *Res. Sports Med.* 28, 529–539. doi: 10.1080/15438627.2020.1784176

Anyadike-Danes, K., Donath, L., and Kiely, J. (2023). Coaches' perceptions of common planning concepts within training theory: an international survey. *Sports Med. Open* 9:109. doi: 10.1186/s40798-023-00657-6

Aquili, A., Tancredi, V., Triossi, T., De Sanctis, D., Padua, E., D'Arcangelo, G., et al. (2013). Performance analysis in saber. *J. Strength Cond. Res.* 27, 624–630. doi: 10.1519/JSC.0b013e318257803f

Bagot, P., Fournier, J. F., Kerivel, T., Bossard, C., Kermarrec, G., Martinent, G., et al. (2023). Visual search strategies of elite fencers: an exploratory study in ecological competitive situation. *J. Funct. Morphol. Kinesiol.* 8:106. doi: 10.3390/jfmk8030106

Boksem, M., and Tops, M. (2008). Mental fatigue: costs and benefits. *Brain Res. Rev.* 59, 125–139. doi: 10.1016/j.brainresrev.2008.07.001

Braun, V., and Clarke, V. (2006). Using thematic analysis in psychology. *Qual. Res. Psychol.* 3, 77–101. doi: 10.1191/1478088706qp063oa

Coyne, J. O. C., Coutts, A. J., Newton, R. U., and Haff, G. G. (2021). The influence of mental fatigue on sessional ratings of perceived exertion in elite open and closed skill sports athletes. *J. Strength Cond. Res.* 35, 963–969. doi: 10.1519/JSC.0000000000003980

Da Costa, Y., Fortes, L., Santos, R., Souza, E., Hayes, L., Soares-Silva, E., et al. (2023). Mental fatigue measured in real-world sport settings: a case study of world class beach volleyball players. *J. Phys. Educ. Sport* 23, 1237–1243. doi: 10.7752/jpes.2023.05152

Díaz-García, J., Filipas, L., La Torre, A., Gómez-Rivera, J., Rubio-Morales, A., and García-Calvo, T. (2023). Mental fatigue changes from regular season to play-offs in semiprofessional soccer: a comparison by training days. *Scand. J. Med. Sci. Sports* 33, 712–724. doi: 10.1111/sms.14301

Diaz-Garcia, J., Gonzalez-Ponce, I., Lopez-Gajardo, M., Van Cutsem, J., Roelands, B., Garcia-Calvo, T., et al. (2021). How mentally fatiguing are consecutive world Padel tour matches? *Int. J. Environ. Res. Public Health* 18:9059. doi: 10.3390/ijerph18179059

Doron, J., and Martinent, G. (2021). Dealing with elite sport competition demands: an exploration of the dynamic relationships between stress appraisal, coping, emotion, and performance during fencing matches. *Cogn. Emot.* 35, 1365–1381. doi: 10.1080/02699931.2021.1960800

Fortes, L. S., Gantois, P., De Lima-Junior, D., Barbosa, B. T., Ferreira, M. E. C., Nakamura, F. Y., et al. (2023). Playing videogames or using social media applications on smartphones causes mental fatigue and impairs decision-making performance in amateur boxers. *Appl. Neuropsychol. Adult* 30, 227–238. doi: 10.1080/23279095.2021.1927036

Gutiérrez-Davila, M., Rojas, F. J., Gutiérrez-Cruz, C., and Navarro, E. (2019). Components of attack response inhibition in fencing: components of attack response inhibition in fencing. *Eur. J. Sport Sci.* 19, 628–635. doi: 10.1080/17461391.2018.1539122

Habay, J., Van Cutsem, J., Verschueren, J., De Bock, S., Proost, M., De Wachter, J., et al. (2021). Mental fatigue and sport-specific psychomotor performance: a systematic review. *Sports Med.* 51, 1527–1548. doi: 10.1007/s40279-021-01429-6

Halson, S. L. (2014). Monitoring training load to understand fatigue in athletes. *Sports Med.* 44 Suppl 2, S139–S147. doi: 10.1007/s40279-014-0253-z

Harmer, P. A. (2019). Epidemiology of time-loss injuries in international fencing: a prospective, 5-year analysis of Fédération Internationale d'Escrime competitions. *Br. J. Sports Med.* 53, 442–448. doi: 10.1136/bjsports-2018-100002

Harper, L. D., and Mccunn, R. (2017). "hand in glove": using qualitative methods to connect research and practice. *Int. J. Sports Physiol. Perform.* 12, 990–993. doi: 10.1123/ijspp.2017-0081

Lam, H. K. N., Sproule, J., Turner, A. P., and Phillips, S. M. (2023). The impact of sprint, middle-distance, and long-distance orienteering races on perceived mental fatigue in national level orienteers. *J. Sports Sci.* 41, 1423–1436. doi: 10.1080/02640414.2023.2273097

Mariano, Y., Martin, K., and Mara, J. (2023). Mental fatigue and technical performance in elite rugby league. *J. Sports Sci.* 41, 584–595. doi: 10.1080/02640414.2023.2228138

Mata, F., Domínguez, R., López-Samanes, Á., Sánchez-Gómez, Á., Jodra, P., and Sánchez-Oliver, A. J. (2021). Analysis of the consumption of sports supplements in elite fencers according to sex and competitive level. *BMC Sports Sci. Med. Rehabil.* 13:50. doi: 10.1186/s13102-021-00278-0

Mckay, A., Stellingwerff, T., Smith, E., Martin, D., Mujika, I., Goosey-Tolfrey, V., et al. (2021). Defining training and performance caliber: a participant classification framework. *Int. J. Sports Physiol. Perform.* 17, 317–331. doi: 10.1123/ijspp.2021-0451

Morris, G. B., Manders, R. J. F., and Hulton, A. T. (2022). Caffeine consumption within British fencing athletes. *Front. Nutr.* 9:999847. doi: 10.3389/fnut.2022.999847

Nordin, Å., Taft, C., Lundgren-Nilsson, Å., and Dencker, A. (2016). Minimal important differences for fatigue patient reported outcome measures-a systematic review. *BMC Med. Res. Methodol.* 16:62. doi: 10.1186/s12874-016-0167-6

Pageaux, B., and Lepers, R. (2016). Fatigue induced by physical and mental exertion increases perception of effort and impairs subsequent endurance performance. *Front. Physiol.* 7. doi: 10.3389/fphys.2016.00587

Roelands, B., and Bogataj, Š. (2024). Optimizing athletic performance through brain endurance training. *Int. J. Sports Physiol. Perform.* 19, 973–974. doi: 10.1123/ijspp.2024-0278

Roelands, B., Kelly, V., Russell, S., and Habay, J. (2021). The physiological nature of mental fatigue: current knowledge and future avenues for sport science. *Int. J. Sports Physiol. Perform.* 17, 149–150. doi: 10.1123/ijspp.2021-0524

Roi, G. S., and Bianchedi, D. (2008). The science of fencing: implications for performance and injury prevention. *Sports Med.* 38, 465–481. doi: 10.2165/00007256-200838060-00003

Russell, S., Jenkins, D., Halson, S., Juliff, L., Connick, M., Kelly, V., et al. (2022a). Mental fatigue over 2 elite netball seasons: a case for mental fatigue to be included in athlete self-report measures. *Int. J. Sports Physiol. Perform.* 17, 160–169. doi: 10.1123/ijspp.2021-0028

Russell, S., Jenkins, D., Halson, S., Kelly, V., Russell, S., Jenkins, D. G., et al. (2022b). Mental fatigue increases across a 16-week pre-season in elite female athletes. *J. Sci. Med. Sport* 25, 356–361. doi: 10.1016/j.jsams.2021.12.002

Russell, S., Jenkins, D., Rynne, S., Halson, S., and Kelly, V. (2019). What is mental fatigue in elite sport? Perceptions from athletes and staff. *Eur. J. Sport Sci.* 19, 1367–1376. doi: 10.1080/17461391.2019.1618397

Russell, S., Johnston, R. D., Stanimirovic, R., and Halson, S. L. (2024). Global practitioner assessment and management of mental fatigue and mental recovery in high-performance sport: a need for evidence-based best-practice guidelines. *Scand. J. Med. Sci. Sports* 34:e14491. doi: 10.1111/sms.14491

Salihu, A., Hill, K., and Jaberzadeh, S. (2022). Neural mechanisms underlying state mental fatigue: a systematic review and activation likelihood estimation meta-analysis. *Rev. Neurosci.* 33, 889–917. doi: 10.1515/revneuro-2022-0023

Tarragó, R., Bottoms, L., and Iglesias, X. (2023). Temporal demands of elite fencing. *PLoS One* 18:e0285033. doi: 10.1371/journal.pone.0285033

Thompson, C., Smith, A., Coutts, A., Skorski, S., Datson, N., Smith, M., et al. (2021). Understanding the presence of mental fatigue in elite female football. *Res. Q. Exerc. Sport* 93, 504–515. doi: 10.1080/02701367.2021.1873224

Tran, Y., Craig, A., Craig, R., Chai, R., and Nguyen, H. (2020). The influence of mental fatigue on brain activity: evidence from a systematic review with meta-analyses. *Psychophysiology* 57:e13554. doi: 10.1111/psyp.13554

Turner, A. N., Kilduff, L. P., Marshall, G. J. G., Phillips, J., Noto, A., Buttigieg, C., et al. (2017). Competition intensity and fatigue in elite fencing. *J. Strength Cond. Res.* 31, 3128–3136. doi: 10.1519/JSC.0000000000001758

Varesco, G., Pageaux, B., Cattagni, T., Sarcher, A., Martinent, G., Doron, J., et al. (2023). Fatigue in elite fencing: effects of a simulated competition. *Scand. J. Med. Sci. Sports* 33, 2250–2260. doi: 10.1111/sms.14466

Varesco, G., Sarcher, A., Doron, J., and Jubeau, M. (2024). Striking a balance: exploring attention, attack accuracy and speed in fencing performance. *Eur. J. Sport Sci.* 24, 1278–1286. doi: 10.1002/ejsc.12176

Weiler, H., Russell, S., Spielmann, J., and Englert, C. (2024). Mental fatigue: is it real?: perceptions from semi-structured interviews with athletes, coaches, and sports psychologists. *J. Appl. Sport Exerc. Psychol.* 32, 14–26. doi: 10.1026/2941-7597/a000033

Yang, W. H., Park, J. H., Shin, Y. C., and Kim, J. (2022). Physiological profiling and energy system contributions during simulated Epée matches in elite fencers. *Int. J. Sports Physiol. Perform.* 17, 943–950. doi: 10.1123/ijspp.2021-0497