frontiers | Research Topics

Insights in movement science and sport psychology 2021

Edited by
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Published in
Frontiers in Psychology
Frontiers in Big Data

ISSN 1664-8714
ISBN 978-2-8325-3514-1
DOI 10.3389/978-2-8325-3514-1

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Insights in movement science and sport psychology 2021

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Citation
Cheron, G., Bertollo, M., Machado, S., eds. (2023). *Insights in movement science and sport psychology 2021*. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-8325-3514-1

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Frontiers in Psychology

TYPE Editorial
PUBLISHED 05 September 2023
DOI 10.3389/fpsyg.2023.1267376

OPEN ACCESS

EDITED AND REVIEWED BY
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RECEIVED 26 July 2023
ACCEPTED 01 August 2023
PUBLISHED 05 September 2023

CITATION
Cheron G, Machado S and Bertollo M (2023) Editorial: Insights in movement science and sport psychology 2021.
Front. Psychol. 14:1267376.
doi: 10.3389/fpsyg.2023.1267376

Editorial: Insights in movement science and sport psychology 2021

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KEYWORDS

sports, ecological, dynamic system, creativity, motor action, emotion, performance

Editorial on the Research Topic
Insights in movement science and sport psychology 2021

The purpose of this Research Topic is to highlight recent research developments in the field of movement science and sports psychology. Even though they are all centered on the practice of sport, the various studies published in this Research Topic demonstrate the great diversity of the themes addressed and the scientific tools used to better understand the foundations of sports activity and its various implications on human health and society in general.

The convergence of ecological, cognitive, and dynamic systems theories to movement science promotes the study of creativity in sports (Zahno and van der Kamp). The old debate of the "motor-action controversy" is revisited to reach a conceptual proposal in which optimal feedback and feedforward predictive controls meet the dynamic systems theory of ecological psychologists, integrating the person-environment relationship.

Basic neurophysiology is here developed around the effects of hypoxia on cognitive performance (Guicciardi et al.) demonstrating that hypoxia increased reaction times, but has no effects on mood state.

Decision-making occupies a central position in the perceptual-cognitive factors and is considered a predictor of talent. This aspect is studied (Hinz et al., 2022) in which experts and non-experts handball players were asked to respond as soon as possible to different attack sequences. This study demonstrates that the experts responded significantly more often with offensive responses than the non-experts. However, the level of expertise does not affect the decision time which decreases with increasing visual information. Six key points (analytical decisions, visual search strategies, creativity, emotions, development, and team coordination) of intuitive decision-making are proposed as determinants of expertise in athletes, referees, and coaches in naturalistic sports (Bossard et al.).

It is now well-recognized that physical exercise (PE) improves not only physical health but also cognitive function, the risk reduction of neurological diseases, and the detrimental effects of aging. In addition, PE improves verbal and graphic fluency and enhances emotional awareness, self-efficacy and self-esteem, the ability to express emotion, and the enhancement of stress management (Passarello et al.).

The effects of real and imagined endurance exercises on sustained attention performance (Wieland et al.) demonstrated that the combination of these two different physiological states (endurance exercise and motor imagery) contribute to better cognitive performance.

The study of the mental representation of overhead throwing movement (Gromeier et al.) demonstrates that the building blocks of mental representations including functional, sensory, spatiotemporal, and biomechanical characteristics of a movement are acquired progressively with age and practice.

Sports injuries and rehabilitation occupy an important sector of human health integrating a large number of medical, individual identity, sport specificity, demographic, and psycho-social factors. In this context, a large cohort of athletes suffering from anterior cruciate ligament injury (McGinley et al.) are studied. It is shown that the Athletic Identity Measurement Scale (AIMS) significantly depends on the sex, years active in sport, activity level, and ACSI-Coachability. Along the same line, a case study (Gomez-Espejo et al.) illustrates the multifactorial aspects of sports injury concerning the emotional and psychological treatment of pain management. Despite the tentative to standardize the methodology for the recovery process following injury and the rapid return to competition, new strategies integrating interdisciplinary approaches are presented (Brooks et al.).

The study of the functional links between working memory and biological motion (Wang et al.) demonstrates that the working memory capacity depends on a large number of factors including the presentation duration, the number of joints, the limb, and the articulations used.

The attractiveness of some sports practices such as the marathon and related touristic activities opens a new field of psychosocial studies of the complex relationships between recreation specialization, life satisfaction, psychological commitment, and social support (Tian et al.).

New recommendations about sudden and unexpected significant declines of performance in the field of "choking under pressure" for individual and team situations are given (Wergin et al.).

The time pressure exerted on adolescent athletes merits to be taken into account in the occurrence of burnout and it is proposed that leisure activities are excellent countermeasures to ensure better functional and mental development and brain maturation in adolescents (Vacher et al.).

Author contributions

GC: Writing—original draft. SM: Writing—review and editing. MB: Writing—review and editing.

Conflict of interest

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

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

Publisher's note

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Hinz, M., Lehmann, N., and Musculus, L. (2022). Elite players invest additional time for making better embodied choices. *Front. Psychol.* 13, 873474. doi: 10.3389/fpsyg.2022.873474

frontiers in Psychology

ORIGINAL RESEARCH
published: 22 March 2022
doi: 10.3389/fpsyg.2022.830555

Working Memory Capacity of Biological Motion's Basic Unit: Decomposing Biological Motion From the Perspective of Systematic Anatomy

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OPEN ACCESS

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

Received: 07 December 2021
Accepted: 24 February 2022
Published: 22 March 2022

Citation:
Wang C, Zhou Y, Li C, Tian W, He Y, Fang P, Li Y, Yuan H, Li X, Li B, Luo X, Zhang Y, Liu X and Wu S (2022) Working Memory Capacity of Biological Motion's Basic Unit: Decomposing Biological Motion From the Perspective of Systematic Anatomy. Front. Psychol. 13:830555. doi: 10.3389/fpsyg.2022.830555

Many studies have shown that about three biological motions (BMs) can be maintained in working memory. However, no study has yet analyzed the difficulties of experiment materials used, which partially affect the ecological validity of the experiment results. We use the perspective of system anatomy to decompose BM, and thoroughly explore the influencing factors of difficulties of BMs, including presentation duration, joints to execute motions, limbs to execute motions, type of articulation interference tasks, and number of joints and planes involved in the BM. We apply the change detection paradigm supplemented by the articulation interference task to measure the BM working memory capacity (WMC) of participants. Findings show the following: the shorter the presentation duration, the less participants remembered; the more their wrist moved, the less accurate their memory was; repeating verbs provided better results than did repeating numerals to suppress verbal encoding; the more complex the BM, the less participants remembered; and whether the action was executed by the handed limbs did not affect the WMC. These results indicate that there are many factors that can be used to adjust BM memory load. These factors can help sports psychology professionals to better evaluate the difficulty of BMs, and can also partially explain the differences in estimations of BM WMC in previous studies.

Keywords: biological motion, working memory capacity, systematic anatomy, change detection paradigm, Cowan's formula, motion animation

Abbreviations: BM, biological motion; WMC, working memory capacity.

INTRODUCTION

Biological motion (BM) refers to the holistic movement behavior of organisms in space (Johansson, 1973; Hoffman and Flinchbaugh, 1982; Kaiser et al., 2010; Jiang and Wang, 2011; Shen et al., 2014). Johansson (1973) was the first to utilize point-light displays (PLD), in which light bulbs were attached to 13 key joints on the body of a model in a black bodysuit. The motions of the model were photographed in a dark environment to obtain information about the movement of the joints. Since this method excluded visual information that were difficult to control at that time, it provided an effective method to acquire experiment materials for the study of BM, and has since been widely used in the study of BM perception (Chang and Troje, 2009; Kröger et al., 2014; Jaywant et al., 2016; Riddell et al., 2017), working memory of BMs (Shen et al., 2014; Ding et al., 2015; Gu et al., 2019; Liu et al., 2019; Guo et al., 2020), BM neurophysiology research (Grossman et al., 2000; Grossman and Blake, 2002; Kröger et al., 2014; Chang et al., 2021), and other fields. PLD enables rapid identification of human motion patterns (Johansson, 1973; Dittrich, 1993), gender (Mather and Murdoch, 1994; Troje, 2002; Troje et al., 2006), and person identification (Troje et al., 2005; Westhoff and Troje, 2007).

As social animals, human beings are driven to recognize and understand the behavior of other individuals from complex BMs every day. From infancy, motion information is very important when discriminating objects (Wood and Wood, 2021). The premise of understanding motion information is to store the BMs—the information carrier—in memory. Therefore, researchers have conducted a large number of studies on working memory. Smyth et al. (1988) and Smyth and Pendleton (1989) found that the working memory capacity (WMC) of movements was from 4 to 5 when there was no simultaneous interference task. Wood (2007) used computer-generated motion animations as experiment materials to measure the WMC of BM using the change detection paradigm, wherein participants were asked to repeat letters to suppress the verbal encoding of movement. Wood's results showed that participants can maintain 2 to 3 BMs in their working memory. He then examined the visual WMC of the identities of agents and their motions, the result of BM WMC in this study were consistent with his previous study (Wood, 2008). Shen et al. (2014) used Wood's experiment as a basis, but changed the experiment materials from computer-generated motion animations to PLD; changed the presentation method of the experiment materials from sequential to simultaneous; and changed the interference task from repeating letters to repeating numerals, which was deemed more suitable for Chinese participants. The results showed that the participants could remember at most 3.02 BMs (Shen et al., 2014).

Previous studies have basically proven that the WMC of BM is about 3; however, the following limitations can be noted in these studies: (1) The amount of experimental materials used has been small. Both Wood's (2007) and Shen et al.'s (2014) studies utilized only seven experiment stimuli, with a maximum of five stimuli presented in a single trial, which may have caused the control of memory load to fail (as detailed by Gu et al., 2019). (2) BMs have been highly conceptualized. Most psychological studies of BMs have only used common actions in life as experiment materials (Vanrie and Verfaillie, 2004; Ma et al., 2005; Wood, 2007), and these motions can be summarized using very concise phrasing. Participants' conversion of these motion patterns into verbal encoding could thus be done almost automatically, and simply repeating letters or numerals could not have completely inhibited participants' verbal encoding. (3) The complexity of BM has been ambiguous. Working memory is a system that is used to store and manipulate limited information (Baddeley, 2012), and its capacity is affected by the complexity of that information. However, previous studies have ignored the influence of this factor on motion in WMC, which partially reduces the ecological validity of the studies' results. (4) The BM information contained in the PLD has been incomplete (Kurz et al., 2020). BM is a typical non-rigid motion (Troje, 2013), and the power of movement comes from the contraction of skeletal muscles. When skeletal muscles contract, their shape and volume change—PLD cannot fully capture this information.

In addition to the above limitations, there is no unified scheme for classifying BMs in psychology, which forces former researchers to generally treat all BMs as homogeneous when studying BM working memory, ignoring the inherent characteristics of each BM. The WMC of these BMs can be better measured only if BMs are divided into several roughly related but relatively independent categories according to their inherent properties. Therefore, we hoped to find a common-sense and scientific way to classify BMs. As it happens, in anatomy (Bo and Ying, 2013; Standring, 2020), there is a set of internationally acknowledged, unified and standardized terms to describe human body shape and joint motions. By adopting these technical terms, we can comprehensively decompose each joint motion into its more fundamental components, which enables us to investigate the underlying features inherent in the BM. Thus, we suggest decomposing BM from the perspective of system anatomy. The concepts of axis and plane are artificially introduced, as follows: (1) The vertical axis is perpendicular to the ground, from top to bottom; (2) the sagittal axis is at an angle of 90° to the vertical axis, from the ventral side to the ventral side; and (3) the frontal axis is perpendicular to the above two axes, in the left and right directions, and parallel to the ground. Further, the three planes correspond to three axes, as follows: (1) the horizontal plane refers to the section that divides the human body into upper and lower parts; (2) the sagittal plane refers to the section that divides the human body into left and right parts, while the section that passes through the center of the human body is called the median sagittal plane; and (3) the frontal plane refers to the section that divides the human body into front and rear parts. The motion of joints is divided into translation, flexion and extension, adduction and abduction, rotation, and circulation. Translation comprises sliding between the two articular surfaces, such as the intercarpal joint. Flexion arises as the angle between the two bones of related joints decreases, while extension is an increase thereof. Medial rotation involves rotating the upper arm forward and toward the body, and lateral rotation entails rotating it back and away from the body; pronation consists of the forearm rotating the back of the hand forward, while supination comprises the back of the hand rotating backward. Circulation consists of the totality of flexion, adduction, extension, and abduction in sequence. Since circumflex movement can be further decomposed, it is not regarded as a basic unit of BM in this study. Using the above decomposition method, any BM can be decomposed into a combination of several basic units.

Here we planned to explore whether the BM WMC remain unchanged regardless of the difficulties inherent in BMs, and if not, what underlying anatomical factors or others might have effects through the following three experiments, and hoped to uncover some approaches to partially overcome the above limitations. Using computer-generated motion animations technique, a technology that has been used several times (Wood, 2007, 2008, 2010; Goldberg et al., 2015; Kenny et al., 2019; Kurz et al., 2020), by which we can strictly control concerned variables and remain irrelevant ones unchanged, thus enabled us develop more BMs with a low extend of conceptualization and then corroborate some hypothesis. First, we hypothesized that the difficulties inherent in the BMs bear some resemblance to each other but is not identical. The genesis of differences might lurk in joint, plate and duration involved in the BMs. In the view of above we conducted experiment 1, in which the concerned variables were strict controlled from the perspectives of systematic anatomy. Second, we hypothesized that BM WMC would not be affected by which side of the limb executes BMs. To confirm the above null hypothesis, we specifically designed an experiment 2 to perform an equivalence test, in which the BMs used were in one-to-one correspondence, the paired motions were identical in model, except for the limb executing the motion. Last but not least, we hypothesized that the more complex of the BMs the less the BM WMC. In the meanwhile, we also want to explore whether the effects of different types of articulation interference task on BM WMC remained unchanged. To this end, both variables above were controlled strictly in experiment 3, a 2 × 2 mixed designed experiment. BMs were divided into two groups in accordance with the anatomical complexity, and verbal articulation interference task was added to experiment 3 as a class of the interference task.

EXPERIMENT 1: THE EFFECT OF PRESENTATION DURATION AND JOINT USE TO EXECUTE MOTIONS ON WORKING MEMORY CAPACITY OF BIOLOGICAL MOTION'S BASIC UNITS

Experiment 1 was based on the experiment conducted by Shen et al. (2014). We decomposed BM into basic units to enhance the difficulty of verbal encoding within a limited time. By increasing the total number of experiment materials, it was more difficult for the participants to verbally encode the complete memory set, so as to avoid the failure of memory load.

Methods

Participants

G*Power 3.1 software (Faul et al., 2009) was used to estimate the sample size. Under the premise of ensuring a medium effect size of 0.25, we set $\alpha = 0.05$, $1-\beta = 0.80$, and calculated the minimum sample size as 88. A total of 90 students from the Air Force Medical University in China were recruited to participate in the study. The student sample comprised 50 male and 40 female, with an average age of 20.12 ± 1.06 years. All participants were divided into six groups according to the between-group variables. They were all right-handed, or right preference mixed–handed (Li, 1983), with normal or corrected-to-normal vision, and naive to the experiment purpose. Informed consent was obtained prior to starting the experiment.

Experiment Design

This experiment adopted a 2 [duration of presentation (s): floating duration ($2 \times n$), fixed duration (2)] × 3 (joint to execute motion: Elbow, shoulder, and wrist) × 5 (set size (n): 1∼5) mixed design, in which the presentation duration and joint used to execute the motion in question were between-group variables, and the set size was the within-group variable. BM working memory performance was the dependent variable.

We followed a variant of the change detection paradigm used by Shen et al. (2014), where the memory array stimuli were presented simultaneously (Fukuda et al., 2010). This variant can effectively overcome the influence of the serial position effect inherent in the sequent-presentation change detection paradigm on the participant's working memory. The primacy and recency effects, widely reported in working memory related research (Agam and Sekuler, 2007; Wood, 2007; Berry et al., 2017), are major contributions to errors. In order to obtain a more accurate estimate, the simultaneous-presentation change detection paradigm was used to measure WMC in our three experiments.

Experiment Materials

In Experiment 1, we chose shoulder, elbow, and wrist movement as the observation object, and kept the hand joints at the distal end of the wrist from relative movement during the motion. Reciprocating motion animations were generated on different planes and different starting positions, respectively. A total of 30 motion animations were generated. All joint movements in Experiment 1 were executed using the right limb of the character model.

Autodesk Maya 2015 three-dimensional modeling and animation software was used to create a human body model that could execute joint motion. The background of the final motion video was gray (RGB: 128, 128, 128), the animation duration was 2 s, the resolution was 240 × 240 pixels, and the frame rate was 30 frames per second. The first five frames kept the starting position unchanged; the 30th frame reached the intermediate stop position and the action was then reciprocated; the 56th frame returned to the starting position; and the last five frames kept the starting position still. **Figure 1A** shows the animation depicting the flexion-extension motion of the right upper limb's elbow joint in the frontal plane; **Figure 1B** shows the adduction-abduction motion of the left upper limb's shoulder joint in the horizontal plane; **Figure 1C** shows the flexion-extension motion of the left upper limb's wrist and elbow joint in the sagittal plane; **Figure 1D** shows a complex motion containing flexion-extension motion of the left upper limb's wrist, elbow and shoulder joint in the sagittal and horizontal plane. See **Supplementary Videos 1–4** for motion animations corresponding to **Figures 1A–D**.

FIGURE 1 | Part of the computer generalized motion animations. **(A)** A flexion-extension motion of the right upper limb's elbow joint in the frontal plane. **(B)** An adduction-abduction motion of the left upper limb's shoulder joint in the horizontal plane. **(C)** A flexion-extension motion of the left upper limb's wrist and elbow joint in the sagittal plane. **(D)** A complex motion containing flexion-extension motion of the left upper limb's wrist, elbow, and shoulder joint in the sagittal and horizontal plane.

The BM experiment materials used in Experiment 1 were all executed by the right limb of the human model, including but not limited to **Figure 1A**. The BM experiment material shown in **Figure 1B** was used in Experiment 2, and the BM experiment materials shown in **Figures 1C,D** were used in Experiment 3, all of them did not appear in Experiment 1.

Experiment Instruments

The experiment stimuli were all presented on a 27-inch LED display with a resolution of 1,920 × 1,080 and a refresh rate of 60 Hz. The participants' eyes were about 70 cm away from the screen, and the size of the motion animation on the screen was about 6.1° × 6.1°. In each trial, between one and five motion animations were randomly presented, distributed on an invisible circle with a radius of about 7.6° positioned at the center of the screen, and the background color was the same as motion video. All stimuli presentations and time controls were conducted using E-Prime 3.0 software.

Experiment Process

The experiment process is shown in **Figure 2**. First, two Arabic numerals were displayed on the screen for a duration of 500 ms. The distance between the two numerals was about 9.8°. The participants were asked to repeat these two numerals consistently and evenly during the trial until pressing a button in response to a numeral detection array. A 300 ms fixation point was then presented. After viewing an empty screen for 150–350 ms (this duration was random), between one and five motion animations were presented on the screen. Depending on the participant group, the duration of the animation was either 2,000 ms or (2,000 × n) ms (in the trial shown in **Figure 2**, if the participant was in the fixed-duration group the motion memory array was presented for 2,000 ms; if the participant was in the floating-duration group, the motion memory array was presented for 8,000 ms). After an empty screen was shown for 1,000 ms, a motion animation appeared in the center of the screen, and the animation stopped automatically after 2,000 ms, with the starting position kept unchanged for 1,000 ms. Participants were asked to judge whether the motion animation of the motion detection array was presented in the motion memory array via button response ("J" for present, "F" otherwise) given within 3,000 ms. If the participant did not make a button response within 3,000 ms, the numeral detection array would be automatically proceeded. The numeral detection array showed an Arabic numeral in the center of the screen. The participant was then asked to determine, within 1,000 ms, whether the number was one of the two numbers that had been repeated during the trial, again via button response ("J" for yes, "F" otherwise). Both the motion detection array and the numeral detection array had a 50% probability of showing a numeral or motion that had not appeared in the memory array.

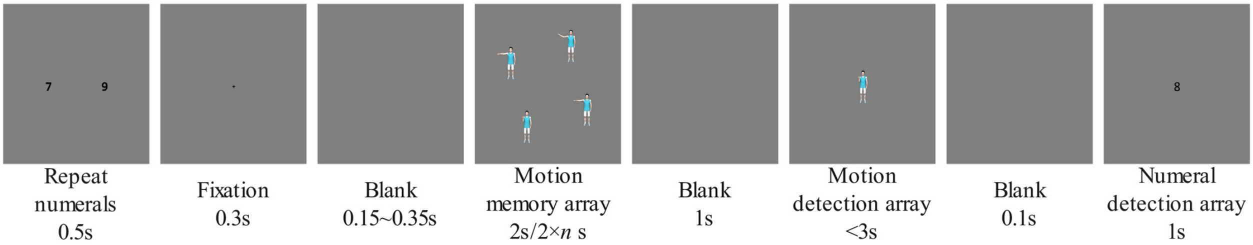

FIGURE 2 | Experiment process. With set size = 4 shown as an example.

The set size of the motion memory array contained a total of five levels. In the formal experiment there were 28 trials for each level, arranged in random order, every 20 trials consisted a group, and a 40-s rest between groups. Before taking part in the formal experiment, participants had to complete at least 10 practice trials to ensure their correct understanding of the experiment process. When the accuracy of the numeral detection array in the last 10 practice trials reached 0.8, the formal experiment was automatically entered. The entire experiment lasted for about 35 min.

Statistical Analysis

Excel 2019 and SPSS 26.0 were used for data collation and statistical analysis. When the accuracy of the participant's numeral detection array exceeded the range of 2.5 times the standard deviation, they were eliminated from the analysis; a total of three participants were excluded based on this criterion.

The widely used Cowan formula in the change detection paradigm was utilized in this study (Wood, 2007; Shen et al., 2014; Guo et al., 2020). The formula is expressed as $k_n = n \times (H_n — F_n)$, where n stands for the set size, k_n for the WMC when the set size is n, H_n to the hit rate, and F_n to the false alarm rate. By incorporating the false alarm rate into the formula, we were able to correct for the influence of guesswork on the accuracy of results (Rouder et al., 2011), and more accurately estimate the individuals' WMC.

Shen et al. (2014) showed that once the set size exceeds the individual's WMC, the performance of working memory tasks under the change detection paradigm shows a downward trend. In order to more accurately estimate the individuals' WMC of BM's basic units, we experiment adopted k_{max} as the participants' estimated WMC of BM.

Results

Handedness Analysis of Participants

A chi-square test of the composition ratio of handedness was performed. Because more than 20% of the cells had a theoretical frequency of less than 5, Fisher's exact test was performed. The results showed that there was no statistically significant difference in the composition of handedness among the various groups (Fisher = 13.466, $p = 0.190$).

Working Memory Capacity of Biological Motion of Each Group

After excluding the data for the three participants whose numeral detection array accuracy was lower than 2.5 times the standard deviations, 87 valid pieces of data remained, with an average of 22.87 (SD, 9.14) practice trials. For the floating-duration group, the accuracy of numeral detection arrays was 94.76% (SD, 0.42%); for the fixed-duration group, the accuracy of numeral detection arrays was 95.28% (SD, 0.40%). The WMC of BM of each group under the condition of different set sizes is shown in **Figure 3**.

Using $k_{\max}$ as a parameter to estimate the participants' WMC of BM, we found that k_{max} (floating × elbow) = 2.95 (SD, 0.71), k_{max} (floating × shoulder) = 2.57 (SD, 0.59), k_{max} (floating × wrist) = 2.57 (SD, 0.63), k_{max} (fixed × elbow) = 2.06 (SD, 0.49), k_{max} (fixed × shoulder) = 2.08 (SD, 0.46), k_{max} (fixed × wrist) = 1.90 (SD, 0.45).

Mixed Analysis of Variance

The mixed analysis of variance (ANOVA) if the WMC of BM under the condition of different set sizes showed that *Mauchly* $W = 0.15$, $p < 0.001$, $\varepsilon = 0.63 < 0.75$. Therefore, the Greenhouse–Geisser method was used to correct the degrees of freedom. The main effect of set size was significant [$F(2.51, 203.12) = 42.88$, $p < 0.001$]; the main effect of presentation duration was also significant [$F(1, 81) = 37.68$, $p < 0.001$]; however, the main effect of joint used to execute motions was not significant [$F(2, 81) = 1.22$, $p = 0.301$]. There was a significant interaction between set size and duration of presentation [$F(2.51, 203.12) = 24.14$, $p < 0.001$], and a significant interaction between set size and joint used [$F(5.02, 203.12) = 2.57$, $p = 0.028$]; however, there was no significant interaction between the duration of presentation duration and joint used [$F(2, 81) = 0.49$, $p = 0.616$]. The interaction among the three was not significant [$F(5.02, 203.12) = 0.72$, $p = 0.606$]. Since the interactions between set size and duration of presentation, and between set size and joint used, were both significant, the simple effect was further investigated.

Figure 4A shows the comparison of the BM WMC for different presentation durations. When the set size was equal to 1 or 2, the difference in presentation duration had no effect on the WMC of BM. When the set size equaled 3 or above, the mean difference gradually increased, and the difference between groups was significant. When the set size was equal to 5, the presentation duration had the greatest impact on the WMC of BM. Under the condition of floating duration, the WMC of BM was 1.33 more on average than under the condition of fixed duration.

Figure 4B shows the comparison between the two presentation duration groups under different set sizes. When the set size equaled 1 or 2, there were significant

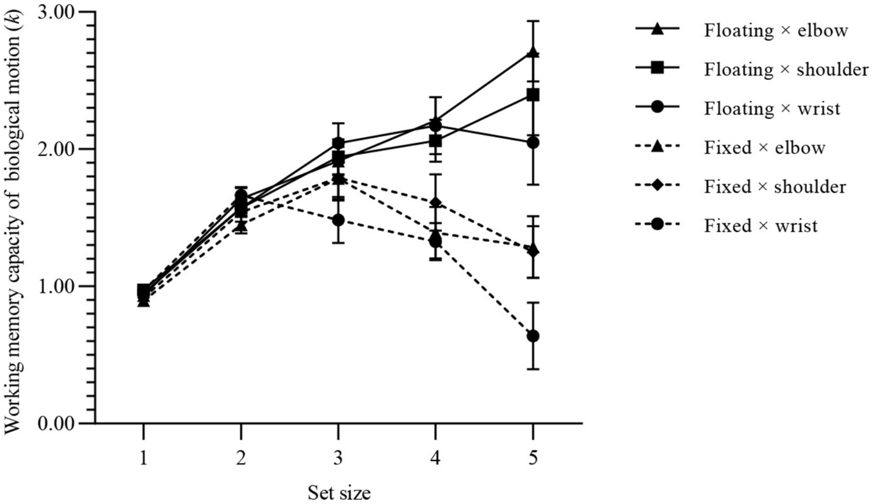

FIGURE 3 | WMC of BM for each group of experiment 1. Values are reported as mean ± standard error.

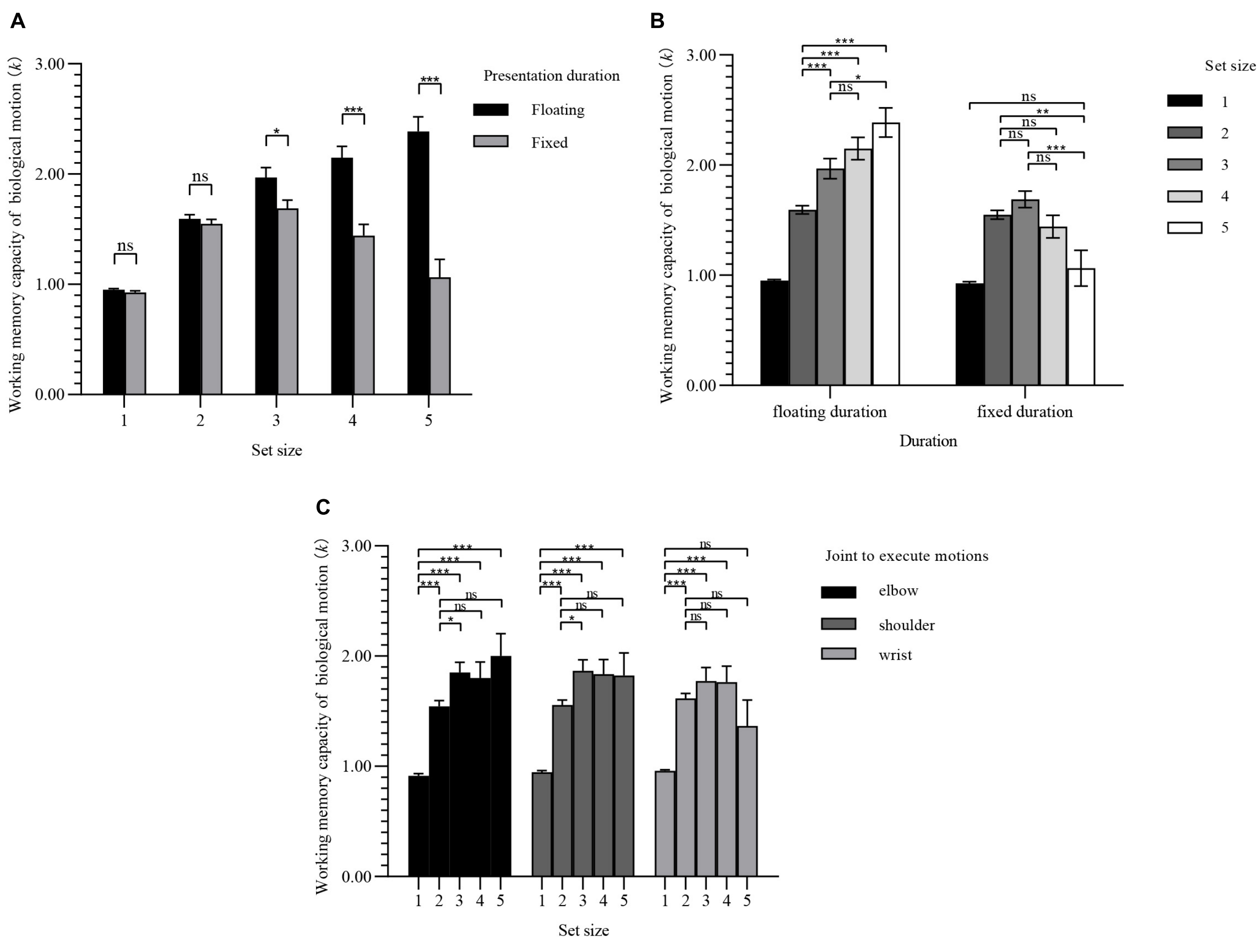

FIGURE 4 | Simple effect results of experiment 1. Values are reported as mean ± standard error. The Bonferroni method was used for multiple test correction. **(A)** Comparison of BM WMC for presentation durations under different set sizes. **(B)** Comparison of BM WMC for set sizes under different presentation durations. **(C)** Comparison of BM WMC for set sizes under different joints to execute motions. ns: not significant; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

differences compared to the other set sizes. When the set size reached 3 or above, the difference between groups disappeared. Under the condition of fixed duration, when the set size was lower than 3 the average difference mean value gradually increased and the differences were significant, and then began to decrease. When the set size arrived at 5, the difference between set size 1 group was no longer significant, and the WMCs of the two groups reached the same level.

Figure 4C shows the comparison of WMC BM when different joints were used to execute motions. The WMC of elbow and shoulder motions reached a higher level when the set size equaled 3, and then remained stable. The WMC of the wrist motions showed an inverted U-shaped change, which reached a peak when the set size was equal to 3, and then began to decrease.

Discussion

In Experiment 1, we simultaneously presented a change detection paradigm supplemented by an interference task of repeating numerals to measure the WMC of BM's basic units, and to explore the effect of presentation duration and joints used to execute motions thereon. The results showed that under the condition of floating duration, the WMC of BM's basic units was significantly greater than that of the fixed-duration condition, which is consistent with the results of Shen et al. (2014). This indicates that, under the condition of fixed duration, the estimation of the WMC of BM was insufficient. There was no significant difference between the WMC of BM executed by different joints regardless of the presentation duration. Under the condition of floating duration, the WMC of BM was 2.5∼3.0; when it came to the fixed-duration condition, this decreased to 1.90∼2.10, and this result bear a close resemblance with Wood's (2008) study.

EXPERIMENT 2: THE EFFECT OF HANDED OR NON-HANDED LIMBS ON THE WORKING MEMORY CAPACITY OF BIOLOGICAL MOTION'S BASIC UNITS

In addition to the joint factor that has been examined in experiment 1, limb is another significant anatomy factor that we are concerned about. In the meanwhile, a large number of previous studies have shown that there is a significant asymmetry in the performance of motor skills between the handed and non-handed limbs (Annett et al., 1974; Amunts et al., 2000; McGrath and Kantak, 2016). This asymmetry is also supported by findings from neuroimage studies of the motor cortex (Volkmann et al., 1998; De Lussanet et al., 2008; Michels et al., 2009; Suzuki et al., 2013). However, there are no studies that have examined whether BM WMC plays a part in the occurrence of this phenomenon. Based on the above two motivations, after examining the influence of joints on BM WMC in experiment 1, we further performed experiment 2 to examine the influence of limbs on BM WMC.

Methods

Participants

The effectiveness analysis and sample size estimation of the two-sample mean equivalence test using a two-stage crossover design were performed by using PASS 15.0 software. A total sample size of 64 achieved 90% power at a 5.00% significance level when the true difference between the means was 0.00, the square root of the within mean square error was 0.51, and the equivalence limits were –0.30 and 0.30. All 45 participants in the floating-duration group in Experiment 1 were reenrolled in Experiment 2, and an additional 43 participants were recruited; of these 88 participants, five dropped out midway. Among the 83 participants who completed Experiment 2, 43 were male and 40 were female, with an average age of 20.52 ± 0.89 years. The experiment adopted a two-stage crossover design. Participants from Experiment 1 were included in the "right-then-left" group, and the rest were included in the "left-then-right" group. All participants were right-handed or right preference mixed–handed (Li, 1983), with normal or corrected-to-normal vision. Informed consent was obtained prior to starting the experiment.

Experiment Design

The experiment adopted a two-stage crossover design. After completing Experiment 1, participants in the right-then-left group accepted into the second stage at 2 weeks intervals, wherein the experiment materials comprised the left limb motion only. The left-then-right group followed the opposite process to that above. Cowan's k_n was the dependent variable.

Experiment Materials

All 30 BM animations used in Experiment 1 were mirror-flipped to obtain the BM animations performed by the left limb. The duration, resolution, frame rate, and other parameters of the animation remained unchanged.

Experiment Instruments

The same instruments were used as in Experiment 1.

Experiment Process

The trial flow of Experiment 2 was the same as the trial process used in the Experiment 1 floating-duration group. In Experiment 2, the right-then-left group received the WMC test with all BMs executed by right limbs in the first stage, and the left-then-right group received the same test but with all BMs executed by left limbs. After a 2-week interval, the order was reversed in the second stage. Each stage lasted about 35 min.

Statistical Methods

Excel 2019, SPSS 26.0 and JASP 0.16 (JASP_Team, 2021) were used for data collation and statistical analysis. When the accuracy of the participant's numeral detection array exceeded the range of 2.5 times the standard deviation they were eliminated from the analysis; a total of two participants whose data exceeded this standard were eliminated based on this criterion. Using the same Cowan formula as in Experiment 1, we calculated the WMC of BM's basic units at different set sizes.

There is no similar previous study to refer to, we used the ratio method suggested by Laster and Johnson (2003) to determine the equivalence margin, α = 0.05, $R_{lowerboundary}$ = 100 (1–2α) %, $R_{higherboundary}$ = 100 (1+2α) %, referring to the value of k_{max} under the condition of floating duration in Experiment 1, we convert the ratio to the effect value. Assuming that k_{max} as 3, the equivalence margin set by this method was 0.3.

In order to give how data quantitatively support a hypothesis (Wagenmakers et al., 2018a; Lakens et al., 2020), we also calculated the Bayes factor with JASP (Wagenmakers et al., 2018b).

Results

Descriptive Analysis

After eliminating the data for two participants as detailed above, 81 valid cases remained. The average practice trial number in the first stage was 23.58 (SD, 10.40), and the accuracy of numeral detection arrays was 94.91% (SD, 2.66%). The average practice trial number in the second stage was 11.85 (SD, 4.22), and the accuracy of numeral detection arrays was 96.08% (SD, 2.23%). The differences between the number of practices (t = 9.40, $p < 0.001$) and the accuracy of numeral detection arrays (t = 3.02, p = 0.003) between the first and second stages were statistically significant. The Cowan's k_n of the two experiment materials at different stages are shown in **Table 1**.

Bayes Factor of Working Memory Capacity Between Handed and Non-handed Limbs

H_0: $\left|\bar{k}_{\text{max}\cdot\text{right}} - \bar{k}_{\text{max}\cdot\text{left}}\right|$ 0.3, H_1: $\left|\bar{k}_{\text{max}\cdot\text{right}} - \bar{k}_{\text{max}\cdot\text{left}}\right|$ 0.3. Because there is no prior knowledge, so we took Cauchy distribution with its scale parameter = 0.707 as the prior model. The equivalence paired t-test showed that there was no significance between$-k_{max\cdot right}$ and$-k_{max\cdot left}$ (t = 0.45, p = 0.653). And there was extremely strong evidence for H_0 (BF_{01} = 338.22).

Discussion

Experiment 2 investigated the difference in the WMC BM between the handed limb movement and the non-handed limb movement. Equivalence test results showed that when 0.3 was taken as the equivalent threshold, both one-side t-tests were rejected; thus, it can be considered that the WMCs of the BM's basic units between groups were consistent. This indicates that whether the motions were executed by handed or non-handed limbs did not affect the WMC of the BM's basic units.

TABLE 1 | Cowan's k_{max} of the two experiment materials at different stages.

Stage	Experiment material	Mean	S.D.
1	Left limb	2.72	0.62
	Right limb	2.71	0.67
2	Left limb	2.77	0.64
	Right limb	2.86	0.82

EXPERIMENT 3: WORKING MEMORY CAPACITY OF COMPLEX BIOLOGICAL MOTIONS

Having examined the effects of joints and limbs on BM WMC, we planned to further examine whether the BM WMC would change under conditions that alter the anatomical complexity of the BM. Therefore, in Experiment 3, we divided BMs into two groups, according to the number of joints and planes contained in BM, in order to test the hypothesis that high-complexity BM is more difficult to remember.

Taking into account the fact that although we have strictly supervised the participants in Experiment 1 and 2 to complete the articulation interference task continuously and vocally, a number of participants still used verbal encoding strategies to remember our purposely designed low-conceptualized BMs, according to a simple survey after experiments.

Thus, in Experiment 3, we added repeating verbs as a new interference task, and added BM with multiple joints and motion planes as experiment materials. We conducted Experiment 3 to test the hypothesis that the WMC of complex BM was inferior compared to that of simple BM.

Method

Participants

A total of 70 participants were recruited—53 male and 17 female, with an average age of 20.46 (SD, 1.46) years. According to the between-group variables, they were divided into four groups. All subjects were right-handed (Li, 1983), with normal or corrected-to-normal vision, and all participants were naive to the experiment purpose. Informed consent forms were collected.

Experiment Design

This experiment utilized a mixed design: 2 [complexity: A group (1 × 1| 1 × 2| 2 × 1), B group (2 × 3| 3 × 2| 3 × 3)] × 2 (interference task: repeat numerals, repeat verbs) × 6 [set size (n): 1–6], BM complexity and interference task comprised the between-group variance, set size was the within-group variance, and the dependent variable was the WMC BM $k_n = n \times (H_n—F_n)$.

Experiment Materials

A total of 60 BM animations were shown, of which 30 motions were executed by the right limb and the remaining 30 motions by the left limb. Motions executed by the respective limbs corresponded to and mirrored each other. According to the number of joints and motion planes involved in the BM, the BMs containing one joint one plane, one joint two planes, or two joints one plane were classified into group A; those containing two joints three planes, three joints two planes, or three joints three planes were classified into group B. Of the 108 candidate body action verbs, 23 with strokes or word frequencies exceeding 1.5 times the standard deviation were removed. This left 85 verbs, of which 15 with the highest word frequency were selected as repeating verbs to comprise the interference task materials. The final 15 verbs (listed in **Table 2**) had an average of 10.00 (SD, 1.96) strokes, and an average word frequency of $11.78/10^5$ (SD, $5.162/10^5$).

TABLE 2 | Verbs repeated by the participant in Experiment 3.

Verbs displayed	Paraphrase	Verbs displayed	Paraphrase
摇	Shake	搬	Carry
抱	Embrace	插	Stick
挂	Hang	刮	Scratch
推	Push	握	Grasp
抽	Whip	捉	Grab
挤	Squeeze	搭	Build
挖	Dig	拣	Pickup
拖	Drag		

Experiment Instruments

The same instruments were used as in Experiment 1.

Experiment Process

The experiment process was the same as that used in the floating-duration group of Experiment 1. The set size contained six levels in total, and each level in the formal experiment comprised 24 trials, with a 40-s rest after every 24 trials.

Statistical Methods

Excel 2019 and SPSS 26.0 were used for data collation and statistical analysis. When the accuracy of the participant's numeral/verb detection array exceeded the range of 2.5 times the standard deviation, they were eliminated from the analysis; a total of five participants were excluded based on this criterion. Under two interference task conditions, a mixed ANOVA was carried out on k_n.

Results

Descriptive Analysis

The WMC of BM for each group is shown in **Figure 5**: k_{max} (verb × group A) = 3.27 (SD, 0.63), k_{max} (verb × group B) = 2.63 (SD, 0.83), k_{max} (numeral × group A) = 2.74 (SD, 0.82), k_{max} (numeral × group B) = 2.78 (SD, 0.98).

Mixed Analysis of Variance

Mauchly's $W = 0.06$, $p < 0.001$, $\varepsilon = 0.60 < 0.75$. Therefore, the Greenhouse-Geisser method was used to correct the degrees of freedom. The main effect of set size was significant [$F(3.02, 184.14) = 24.81$, $p < 0.001$]; the main effect of complexity was significant [$F(1, 61) = 8.68$, $p = 0.005$]; the main effect of interference was not significant [$F(1, 61) = 2.09$, $p = 0.153$]; the interaction between set size and complexity was marginally significant [$F(3.02, 184.14) = 2.37$, $p = 0.072$]; the interaction between set size and interference was not significant [$F(3.02, 184.14) = 0.60$, $p = 0.618$]; the interaction between complexity and interference was not significant [$F(1, 61) = 0.93$, $p = 0.339$]; the interaction between these 3 variance was not significant [$F(3.02, 184.14) = 0.73$, $p = 0.535$]. Considering that this is an exploratory study, marginal significance can also make us more convinced of the alternative hypothesis to a certain extent (Pritschet et al., 2016), so we further conducted a mixed-design ANOVA under different interference task conditions.

Mixed ANOVA Under the Condition of Repeating Numerals

Under the condition of repeating numerals, Mauchly's $W = 0.04$, $p < 0.001$, $\varepsilon = 0.57 < 0.75$. The same method was used to correct the degrees of freedom. The main effect of set size was significant [$F(2.83, 79.34) = 8.47$, $p < 0.001$]; but the main effect of complexity was not significant [$F(1, 28) = 1.44$, $p < 0.240$]; the interaction between set size and complexity was also not significant [$F(2.83, 79.34) = 0.46$, $p = 0.700$].

Mixed ANOVA Under the Condition of Repeating Verbs

Under the condition of repeating verbs, Mauchly's $W = 0.06$, $p < 0.001$, $\varepsilon = 0.58 < 0.75$. The same method was used to correct the degrees of freedom. The main effect of set size was significant [$F(2.92, 96.21) = 18.50$, $p < 0.001$]; the main effect of complexity was significant [$F(1, 33) = 10.705$, $p = 0.030$]; and the interaction between set size and complexity was also significant [$F(2.92, 96.21) = 3.13$, $p = 0.030$]. The simple effect was further investigated.

Figure 6A shows the simple effect of complexities under the condition of different set sizes. Under the repeating verbs condition, when the set size ≥ 3, there was a significant difference in BM WMC between complexities.

The simple effect of set sizes under different complexities is shown in **Figure 6B**. The WMC of BM of group A increased as the set sizes increased, and there was a significant difference compared with the overall average increment. However, group B showed a steady trend after the set size reached 2.

Discussion

Under repeating numerals conditions, complexity had no significant effect on WMC BM, but under repeating verbs conditions the negative effect of complexity on WMC BM was significant. This suggests that participants were affected by the repeating verb interference task when encoding group B's BM. This indicates that the BM verbal encoding process consumed few cognitive resources; the simultaneously repeating numerals task could not completely suppress the verbal encoding of BM; and the repeating verbs interference task suppressed verbal encoding to a greater extent. Further cross-cultural research is needed to explore whether this phenomenon is limited to people that use ideograms like Chinese characters.

GENERAL DISCUSSION

From the perspective of systematic anatomy, this study conducted three experiments to identify the influencing factors of WMC of BM's basic units.

This study adds the following to research related to BM working memory. First, we've explored the underlying anatomical factors which have effects on BM WMC. To our knowledge, this is the first time that anatomical basis has been used in psychology research to decompose BMs, thanks to the fact that this classification method is very mature, well-established and universally recognized in the field of anatomy

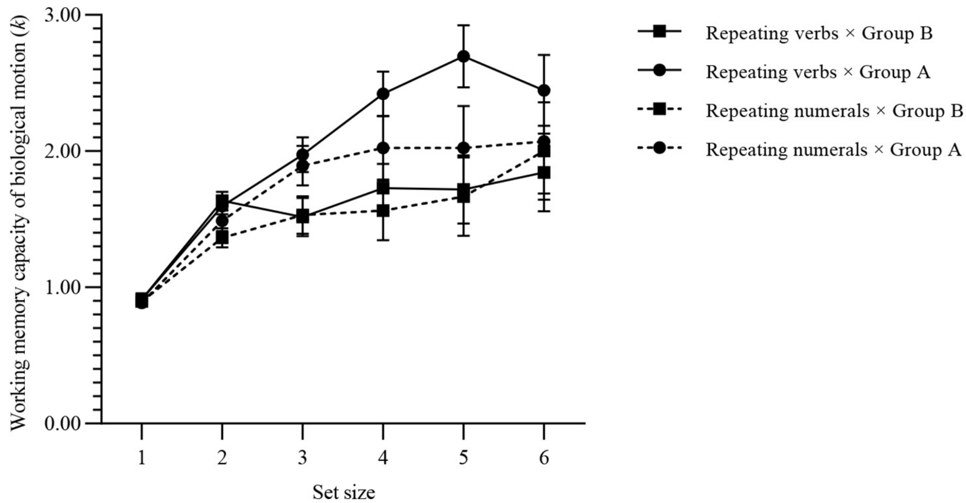

FIGURE 5 | WMC of BM for each group of experiment 3. Values are reported as mean ± standard error.

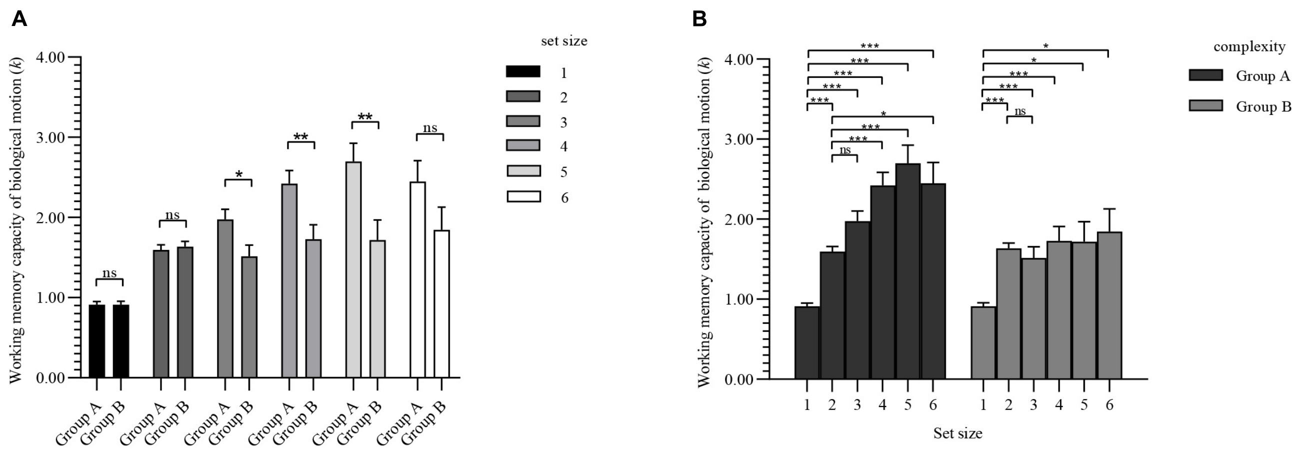

FIGURE 6 | Simple effect results of experiment 3. Values are reported as mean ± standard error. The Bonferroni method was used for multiple test correction. **(A)** Comparison of BM WMC for two complexities under different set sizes. **(B)** Comparison of BM WMC for set sizes under different complexities. ns: not significant; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

(Bo and Ying, 2013; Standring, 2020), it makes it possible for us to apply it to the study of BM in the field of psychology, especially when it comes to motions executed by human body. Second, BMs used in our study was low-conceptualized and sufficient in amount due to the adoption of anatomical decomposing. The above two points make it more difficult for the participants in our experiments to reasonably encode BMs within a limit time, and partially overcome the imperceptible verbal encoding in the previous studies (Gu et al., 2019). It is a potential approach to further preclude the influence of the verbal encoding of the participants in the BM related studies in addition to the concurrent articulation interference task. Furthermore, the adoption of computer-generated motion animation enabled us to strictly control the irrelevant variables, including hairstyle, mutable expression and fluttering clothing, while a clear figure with non-rigid motion (Troje, 2013) can be completely preserved. This brought the behavior of the participants in our study closer to how they would react when they saw real actions, which can partially improve the external validity of the conclusions of our study.

Effect of Presentation Duration on the Working Memory Capacity of Biological Motion's Basic Units

The results of Experiment 1 indicate that under the fixed-duration condition, the WMC of BM's basic units was underestimated; this is consistent with previous studies (Shen et al., 2014). Such findings might be attributed to the limited time given to participants, which caused them to fail to encode all BMs. The more BMs left uncoded, the more speculation may have occurred and the closer the resulting false alarm rate was to random levels. When the impact to WMC of false alarm rate was larger than that of set size, Cowan's k_n began to drop. However, under the floating-duration condition, the decreasing tendency disappeared and the WMC was stable at a higher level. This shows that under floating-duration conditions, increases in the false alarm rate and the set size offset each other's influence on Cowan's k_n.

Effect of Joint Use on the Working Memory Capacity of Biological Motion's Basic Units

Although there were no significant differences between the WMC of the BMs executed by the three joints, it is worth noting that the peaks of the WMC of the BM's basic units did not appear at the same time. The BM executed by the wrist was the first to reach the peak of capacity, and then began to decline. The BMs executed by the elbow and shoulder peaked following the wrist joint, but Cowan's k_n did not show a significant decrease. This indicates that the corrected recognition rate (Snodgrass and Corwin, 1988) for judging the BM executed by the wrist was lower than that of the elbow and shoulder when the number of BMs presented simultaneously was larger than three. As mentioned above, the trend of Cowan's k_n reflected the change in false alarm rate under different conditions. It can thus be inferred that wrist movements are more difficult to remember, so individuals in our experiments had to guess when judging. As a result, when the set size exceeded the limit of the WMC of BM's basic units, the degree of guessing with regard to the wrist motion was greater, which caused a rapid decrease in the WMC. This is in line with results found by Liu and Ku (2017). In short, the more BMs executed by wrist, the less accurate the memory. Our results also supported the discrete, fixed-resolution representation model of working memory (Zhang and Luck, 2008).

Effects of Handed and Non-handed Limbs' Motion on the Working Memory Capacity of Biological Motion's Basic Units

The equivalence test results of Experiment 2 suggest that whether motion is executed by handed or non-handed limbs has no effect on the WMC of BM. A large number of previous studies have shown that there is significant asymmetry in the performance of motor skills in handed vs. non-handed limbs (Annett et al., 1974; Amunts et al., 2000; McGrath and Kantak, 2016). This asymmetry has also been found in neuroimage studies (Volkmann et al., 1998; Suzuki et al., 2013). Combined with the results of this study, the difference in the performance of motor skills learning between handed and non-handed limbs is mainly caused by physiological conditions, rather than differences in memory.

Effect of Complexity and Interference Task on the Working Memory Capacity of Biological Motion

The results of Experiment 3 show that conducting the repeating verbs interference task simultaneously when measuring the complex BM WMC had a significant negative impact on the performance of the main task. This phenomenon was not found when participants memorized simple BMs, nor was it found under conditions of simultaneously repeating numerals. Previous studies have confirmed that simultaneous articulatory suppression tasks can inhibit individuals from verbal coding of BM (Vogel et al., 2001; Curby and Gauthier, 2007; Shen et al., 2014). The results of Experiment 3 suggest that the effect of the repeating verbs interference task in suppressing BM's verbal encoding was inconsistent with the repeating numerals interference task. Repeating numerals could suppress the verbal encoding of BM in a relatively stable manner, regardless of the complexity of the BM to be maintained. However, the suppression effect of repeating verbs on verbal encoding of BM was regulated by the complexity of the BM.

The basic assumption of the dual-task paradigm is that if two tasks compete for the same limited cognitive resources, task performance will decline. Under the condition of repeating verbs, the WMC of simple BMs was significantly higher than that of complex BMs. This shows that complex BMs required more cognitive resources for verbal encoding, which means that complex BMs are more difficult to remember.

In these three experiments, we focused on the upper limbs with a greater range of motion (Bo and Ying, 2013; Standring, 2020), hoping to compromise between the representativeness and complexity of the experiment materials, and thus the trunk and lower limbs were irrelevant variables to control. This compromise results in limited external validity. BMs in previous studies required movements of various parts of the body to execute specific movement patterns or reach specific spatial locations. The BMs in our study only had upper limb movement, with the trunk and lower limbs remaining stationary, and had no specific purpose. Although some experiment results corroborated with previous studies (Wood, 2007, 2008; Shen et al., 2014), we are still unable to deduce whether the conclusion that BM WMC is associated with anatomical factors can be generalized to full-body motions. Therefore, we planned to investigate the effect of anatomy factors on the WMC of lower limb and trunk motions in future studies.

In summary, the results of this study suggest that: First, individuals can maintain two to three basic units of BM in working memory. Second, there is no difference between handed and non-handed limbs. Third, the more the wrist joint moves, the more inaccurate the memory of the upper-limb BMs. Finally, complex BMs are more difficult to remember. These results prompt us, BM WMC could be affected by inherent anatomical factors in BMs. In another word, it is unstable. Based on the conclusion of our research, we suggest that subsequent research on BM working memory should pay more attention to more detailed description and classification of the BMs used. In the meanwhile, this research can also provide a reference in the training of some certain populations, including gymnasts, diving athletes, martial arts athletes even pilots. In the process of training of these groups, coaches can modify the difficulty of movements they will demonstrate by controlling any of the above factors, through which the teaching progress may be mastered more objectively, and the training time for different movements can be set more targeted.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Medical Ethics Committee of the First Affiliated Hospital of the Air Force Medical University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CW wrote the original draft. CW, YeZ, CL, and SW contributed to design of the study. WT translated and polished the first draft. YH, PF, and YL conducted part of the experiment. CW, HY, XiL, and BL performed the statistical analysis. XeL and YnZ gave valuable comments on the revision of experiment material. XfL and SW contributed to manuscript revision. All authors have read and agreed to the submitted version of the manuscript.

FUNDING

This work was supported by Research on Major Issues in Aviation Medicine (2019ZTD04), Research on Key Technologies and Methods of Psychological Selection of New Talents (BKJ19J021), Establishment of Important Cognitive Ability Training System (KJ20182A030138), and Fourteenth Five-Year Key Issues (BKJ21J013).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.830555/full#supplementary-material

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ORIGINAL RESEARCH
published: 05 April 2022
doi: 10.3389/fpsyg.2022.854208

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Differences in Decision-Making Behavior Between Elite and Amateur Team-Handball Players in a Near-Game Test Situation

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OPEN ACCESS

Edited by:
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Federal University of Santa Maria, Brazil

Reviewed by:
Miguel Pic,
South Ural State University, Russia
Sean Müller,
Federation University Australia, Australia

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

Received: *13 January 2022*
Accepted: *04 March 2022*
Published: *05 April 2022*

Citation:
Hinz M, Lehmann N, Aye N, Melcher K, Tolentino-Castro JW, Wagner H and Taubert M (2022) Differences in Decision-Making Behavior Between Elite and Amateur Team-Handball Players in a Near-Game Test Situation. Front. Psychol. 13:854208. doi: 10.3389/fpsyg.2022.854208

Athletic features distinguishing experts from non-experts in team sports are relevant for performance analyses, talent identification and successful training. In this respect, perceptual-cognitive factors like decision making have been proposed to be important predictor of talent but, however, assessing decision making in team sports remains a challenging endeavor. In particular, it is now known that decisions expressed by verbal reports or micro-movements in the laboratory differ from those actually made in on-field situations in play. To address this point, our study compared elite and amateur players' decision-making behavior in a near-game test environment including sport-specific sensorimotor responses. Team-handball players ($N = 44$) were asked to respond as quickly as possible to representative, temporally occluded attack sequences in a team-handball specific defense environment on a contact plate system. Specifically, participants had to choose and perform the most appropriate out of four prespecified, defense response actions. The frequency of responses and decision time were used as dependent variables representing decision-making behavior. We found that elite players responded significantly more often with offensive responses ($p < 0.05$, odds ratios: 2.76–3.00) in left-handed attack sequences. Decision time decreased with increasing visual information, but no expertise effect was found. We suppose that expertise-related knowledge and processing of kinematic information led to distinct decision-making behavior between elite and amateur players, evoked in a domain-specific and near-game test setting. Results also indicate that the quality of a decision might be of higher relevance than the required time to decide. Findings illustrate application opportunities in the context of performance analyses and talent identification processes.

Keywords: sensorimotor decisions, expertise, decision time, motor responses, perceptual-cognitive skills

INTRODUCTION

Features that set apart the sports experts from the non-experts have been a topic of considerable research efforts during the last years. In this regard, it has been proposed that physical (e.g., anthropometric), physiological, psychological, sociological, technical, and tactical factors discriminate between athletes of different levels of expertise (Burgess and Naughton, 2010; Sarmento et al., 2018; Piggott et al., 2020). Most emphasis in research has been placed on studying physical aspects and biomotor abilities (such as speed, strength, power, agility, and endurance), although recent studies suggest that the predictive validity of these factors regarding performance and talent identification is limited, especially when they are looked at in isolation (Wagner et al., 2016, Wagner et al., 2019, 2020; Bennett et al., 2018; Bergkamp et al., 2019). This might be due to the fact that these particular predictors are not representative enough with respect to the contextual constraints of on-field behavior (Bergkamp et al., 2019). To overcome this problem, multidisciplinary approaches have been suggested to diagnose future performance and talent. Particularly, the need to focus more on the psychological and perceptual-cognitive components of athletes has been highlighted in recent studies (Bangsbo, 2015; Woods et al., 2016; Bennett et al., 2018; Bergkamp et al., 2019; Sherwood et al., 2019; Piggott et al., 2020). Indeed, mounting evidence suggests that perceptual-cognitive skills such as decision making constitute a performance-discriminating component in team-sports (Mann et al., 2007; Travassos et al., 2013; Silva et al., 2020; Ashford et al., 2021).

It is against this background that the development and evaluation of tests to diagnose perceptual-cognitive skills and expertise in athletes has gained more and more attention in the last years. A commonly used approach to study sport-specific decision making is the so called temporal occlusion paradigm (Jones and Miles, 1978). Essentially, studying decision making with this approach involves presenting video clips of selected game sequences on a screen, and subjects watch these clips while usually being in a sitting or standing position (Travassos et al., 2013 for details). After the end of the video sequences, subjects are mostly required to verbalize their intended response for the game situation in question, or to verbalize their generated options (Johnson and Raab, 2003; Raab and Johnson, 2007; Raab and Laborde, 2011). Decision making in real life evolves from a complex and uncertain context (especially in team-sports), requiring athletes to constantly process information while acting under time and information constraints (Travassos et al., 2012; Kinrade et al., 2015). Against this background, it appears problematic to not consider the specific environment in which the players actually perform, and particularly to neglect the impact of sensorimotor interactions in decision making (Burk et al., 2014; Raab, 2014). Recent examinations in netball (Bruce et al., 2012), and soccer (van Maarseveen et al., 2018a) clearly suggest that the decision-making performance in perceptual-cognitive tests (using verbal reports, button press, or micro-movements) differs from actual real-world decision-making performances, thus hampering the ecological validity of findings (Araújo et al., 2007; Ashford et al., 2021). Taken together, these studies highlight that assessing verbal or micro-movement responses (Travassos et al., 2013) might be not sufficient to predict on-field performance, let alone to detect talents. Notwithstanding, there is also evidence in perceptual-cognitive research which showed that uncoupled perception-action responses, given either verbally or by keystroke, are similar (Farrow et al., 2005) or even more accurate (Ranganathan and Carlton, 2007) than coupled perception-action responses, requiring sport-specific action responses. It was also found that when observers are static in computer-based experiments, the motor regions of the brain are still linked to the perceptual information picked up (Aglioti et al., 2008). In team-handball (Huesmann et al., 2021), compared the anticipation performances of advanced, intermediate, and novice team-handball goalkeepers in a perception-action artificial (verbal responses) and simulated (motor responses) condition with. The authors revealed overall superior performances (higher prediction accuracies) in the artificial, verbal response condition, outlining that the evidence regarding the necessity of the involvement of motor components seems mixed. However, when capturing expert performance in decision making, expertise effects are most pronounced when the participants actually performed actions under *in situ* task constraints (Travassos et al., 2013) in realistic test paradigms under field conditions (Mann et al., 2007).

Since the discrepancy between decision making in decoupled vs. coupled processes of perception and action in task designs has only recently become known, there are only a few studies assessing decision making in near-game test conditions with requirements to perform a sport action (Travassos et al., 2013). One notable example is the study by Magnaguagno and Hossner (2020) in team-handball, which investigated decision making in a performer environment by using virtual reality. Specifically (Magnaguagno and Hossner, 2020), presented 1 vs. 1 video sequences between a defending teammate and a left or right back attacker, respectively, ending in either a successful or a lost defense action of the teammate. The participants were put into an assisting role as a defender next to the 1 vs. 1 situation. Depending on the teammates' either weak or strong defending behavior, participants had to decide (based on their anticipatory performance) whether to move sideways for tackling the attacker (in case the weak teammate has lost his duel), or whether to stay in the passive position (in case the strong teammate successfully defended the attacker). The authors found expertise effects in response correctness, showing that expert players responded more appropriately on a lost 1 vs. 1 duel of the respective defending teammate than the near-expert players. However, response correctness simply based on the decision whether to stay passive or to tackle. Further options for defense actions, e.g., provoked by additional varying attack sequences, were not regarded. Also, the respective time of responses (decision time) was not recorded, even though decision time is thought to be an important metric of decision making (Vaeyens et al., 2007; Raab and Laborde, 2011; Ratcliff et al., 2016; Seale-Carlisle et al., 2019).

In the present study, we investigated whether decision-making in a near-game performer environment would differ between expert and near-expert athletes. To this end, we used a team-handball specific sensorimotor decision-making task with varying attack sequences based on the temporal occlusion approach (see Jones and Miles, 1978 for details). We have previously shown that this test setup is sufficiently reliable to study decision making (Hinz et al., 2021), and by comparing experts vs. near-experts we now undertake the next step to discover the potential usefulness of this test to distinguish expert vs. non-expert performance. This test setup involves both domain-specific motor responses (as compared to, for example, button press) and the opportunity to choose among various response options (as compared to "either-or decision making"). We also recorded decision times which allowed us to study whether expert and near-expert players would initiate a different defense action (e.g., a "proactive" behavior like tackling vs. a "passive" behavior like blocking) in response to identical visual information, and whether there are differences in the accompanying decision times. In order to use representative task constraints (Travassos et al., 2013), we also investigated the decision-making performances in right- as well as left-hander attack sequences, due to handedness advantages in favor of left-handers in sport (Hagemann, 2009; Loffing et al., 2015).

MATERIALS AND METHODS

Carrying out between-group comparisons with multiple choices for responses entails difficulties in estimating *a priori* effect sizes. Therefore, our sample size recruitment complied with sub-sample sizes from earlier between group investigations in this field (e.g., Raab and Johnson, 2007; Zoudji et al., 2010; Bruce et al., 2012).

The sample of participants consisted of 44 male team-handball players (M_{age} = 19.11 years; SD = 6.56 years). Two teams (n = 22; M_{age} = 17.59 years, SD = 3.67 years) were recruited of a professional youth academy of a first league team-handball club of the German Handball Federation. All players competed in the highest possible league within their age category. Players of these teams performed a minimum of 14 h training per week with one competition match at weekends. All athletes practiced team-handball for at least 8 years. Based on the recommendations of Swann et al. (2015) how to classify expertise level in sports science, players of the two teams can be considered as elite level players. The players of the other two teams (n = 22; M_{age} = 20.71, SD = 8.54) were recruited from non-professional, local league teams within their age categories. All athletes performed 4 h of training per week with one competition match at weekends, and players practiced team-handball between 2 and 22 years. According to the definition of Room (2010), who defines a player, "who takes part in sport for pleasure, as distinct from a paid professional" as amateur player, the athletes of these two teams can be considered as amateur level players. Differences in age between both groups were not significant (p = 0.952).

The experiment was conducted during the first half of the championship season 2020/21, in October and November. At that time, all teams had a normal weekly training and match schedule, without being affected or restricted by any local or federal COVID-19 regulations. During the test, participants were instructed to perform with a maximum effort. Injuries lead to exclusion of the study. Prior to their participation, all participants and legal guardians were informed about the purpose, risks, and benefits of the study. All participants had to give a written informed consent before the first test day. Participants were not identifiable from the test results. The study protocol was approved by the local ethics committee from the Otto von Guericke University Magdeburg and met the requirements of the Declaration of Helsinki and its later amendments.

All tests were conducted on the contact plate system SpeedCourt® (Q12 PRO mobile, GlobalSpeed, Hemsbach, Germany) which enables sport-specific motor responses to temporally occluded videos. As a basis for profound interpretations of envisaged results, we used the test setup from a previous study (Hinz et al., 2021), which was introduced and checked for basic psychometric properties (reliability), using four team-handball specific attack actions for intra- (cross-sectional) and inter-session (longitudinal) agreement of the motor response choices and times. Significant Cohen's (0.44–0.54) and Fleiss' (0.33–0.51) kappa statistics (Fleiss and Cohen, 1973) revealed moderate agreement level of motor responses. Please refer to this paper for detailed explanations regarding test construction and item analyses. In the study at hand, we used the identical test setup and video stimuli, along with the same mapping of the four choice responses (forward/tackling response; sideways left or right movements; blocking/passive behavior) to the contact plates on the SpeedCourt®.

The experimental scenario consists of *Breakthrough*, *Standing throw*, *Jump throw*, and *Pass* videos, which were temporally occluded within a general time frame of *ball was passed to attacker* (t_6) and *obvious end of attack* (t_0), with time intervals of 200 ms (t_6 = −1200 ms, t_5 = −1000 ms, t_4 = −800 ms, t_3 = −600 ms, t_2 = −400 ms, t_1 = −200 ms, t_0 = 0 ms). The duration of each video clip was not longer than 2 s (stopping at t_0). Dummy trial videos, showing too ambiguous attack actions for an appropriate defense response, were included in the test scenario, aiming at avoiding expectation effects in response behavior (Anderson, 1983). Due to handedness advantages in favor of left-handers in sport (Hagemann, 2009; Loffing et al., 2015), all video clips were mirrored.

The videos were sized 1280 × 720 pixels (width × height) and the test scenario was implemented by using *Lazarus* (Version 2.0.10) software. In total, 112 right- and left-handed attack video clips were presented to the subjects during the measurement procedures.

The test procedure always started on the marked 7 m line on the central contact plate of the SpeedCourt®. In this starting position, a 3 s countdown appeared on the screen, followed by a video stimulus showing an attack action. The aim was to respond as intuitive and as realistic as possible after the video presentation ended. Subjects were then returned to the starting position to prepare for the next countdown. Subjects were instructed that the motor response to a video stimulus should replicate their first intuition for a defense response that came to their mind while watching the video. Too early or unintended given responses were marked for later exclusion. No information about decision performance or the remaining number of videos was provided to the subjects.

In relation to the Bayesian integration framework (Vilares and Kording, 2011; Gredin et al., 2020), all subjects received the same team-handball specific instructions (stable priors) about the attacker's action tendencies, the defense tactics, and the match status. Stable context priors *via* action tendencies were provided, meaning that the center back player in the video can be considered as an allrounder or playmaker, being able to put high pressure on the defense through a variety of long and near range standing and jump throws, strong one-on-one actions, and high-quality passing. Tactical priors were also supplied to the subjects. More specifically, they were instructed to put themselves in the position of the central block defender in a classic man-to-man defense without teammates, or other opponents than the attacker in the video/situation. The match status was pre-specified as the 50th minute of play (of 60 min in total) and the game score was tied.

Following the instructions, subjects performed 10 familiarization trials, showing a selection of occluded attack actions in randomized order. After familiarization, the test started with a block of right-hander video stimuli followed by a left-hander block, interspersed by a short break of approximately 5 min. Within each block, the videos were presented in quasi-randomized order, starting at occlusion t_6 (fewest information) and ending at t_0 (full information) videos. The test duration was approximately 35 min.

Analysis

All data used in this study was recorded from the contact plates of the SpeedCourt® system. Dependent variables were response frequency (categorical) and decision time (in ms). A motor response was registered when leaving a contact plate and entering a new/the same contact plate. Decision time was defined as the time elapsed from the end of the video presentation to the beginning of the motor response (force on plate > 80 N).

We applied an outlier detection procedure based on decision time data, as proposed by Leys et al. (2013). Specifically, we started by calculating the absolute deviation around the time sample median for each occlusion point in each action. A moderately conservative rejection criterion of 2.5 times the median absolute deviation (MAD) below or above the median was defined. In other words, individual time data was categorized as outliers if their time value fell outside the predefined rejection criterion. If outliers of data points were detected, all related variables (i.e., choice of motor response, decision time) of the respective case were discarded from further statistical analysis.

Unless otherwise stated, the Statistical Package for the Social Sciences Version 26 (SPSS Inc., Chicago, IL, United States) was used for inferential statistics in the following analyses. Statistical tests of significance carried out throughout the manuscript were performed two-sided, and the significance level was set to $p < 0.05$.

For the characterization of distinctions in decision making behavior between elite and amateur players, we compared the frequencies of the occurrence of each motor response (i.e., forward/tackling; passive/blocking; sideways right; sideways left) at each occlusion point by means of a Chi-squared test. The magnitude of Chi-square-based associations was evaluated using the effect size Phi (φ) (Kim, 2017). Phi was calculated by dividing the Chi-square value by the sample size n and then taking the square root, yielding a value ranging from −1 to 1. The magnitude of φ can be interpreted using the following thresholds (Cohen, 1988; Kim, 2017): $0.1 < |\varphi| < 0.3$ "small," $0.3 < |\varphi| < 0.5$ "medium," and $|\varphi| > 0.5$ "large" effect. Note that negative values for φ denote higher frequencies in the elite player group and reverse for positive values.

To summarize evidence over the seven Chi-squared tests (i.e., occlusion points t_6–t_0) belonging to each motor response and each action, partial two-sided p-values were combined into a single global p-value using Fisher's Chi-square combination (Fisher, 1932):

$$\chi^2 = -2\sum_{i=1}^{k} \ln\left(p_i\right)$$

In case the combined null hypothesis of no between-group difference whatsoever is rejected, one can conclude that at least one of the partial null hypotheses is false. Put another way, Fisher's combination allows to combine multiple pieces of evidence to yield a style of meta-analytic result. Odds ratios (OR) with a 95% confidence interval (CI) were calculated (as described by Bland and Altman, 2000) by pooling all responses in each occlusion in the single attacks, in order to obtain summarized effect sizes of Chi-square combinations. Note that Fisher's combination was only applied if the direction of between-group differences was consistent across all occlusion points. The above was done using the *poolr* package (Cinar and Viechtbauer, 2021) running in *R* v3.6.1 (R Core Team, 2013).

In our previous study (Hinz et al., 2021), as expected, we observed quicker response times as a function of increasing amount of visual information. However, it remains to be determined whether experts and amateurs differ with respect to decision times. To this end, we subjected decision time data to a 2 (elite and amateur level) by 7 (occlusion time point t_6–t_0) repeated measures analysis of variance (ANOVA). Before ANOVAs were calculated, all data was checked for normality using the Kolmogorov–Smirnov test.

RESULTS

Significant between-group differences of the response frequency distributions are shown in **Figure 1**. Significant effects of expertise were present in the left-handed Breakthrough and Pass only. Full illustrations of response frequency and distribution in all attacks, as well as individual Chi-square statistics, are provided in **Supplementary Figures 1, 2** and **Supplementary Tables 1**, **2**.

Irrespective of group, visual inspection of frequency distributions shows dynamically changing response patterns over occlusion points, most likely due to the varying amount of visual information provided about the attacker's action. As indicated by significant results of Fisher's combination, the elite players responded significantly more often with forward/tackling

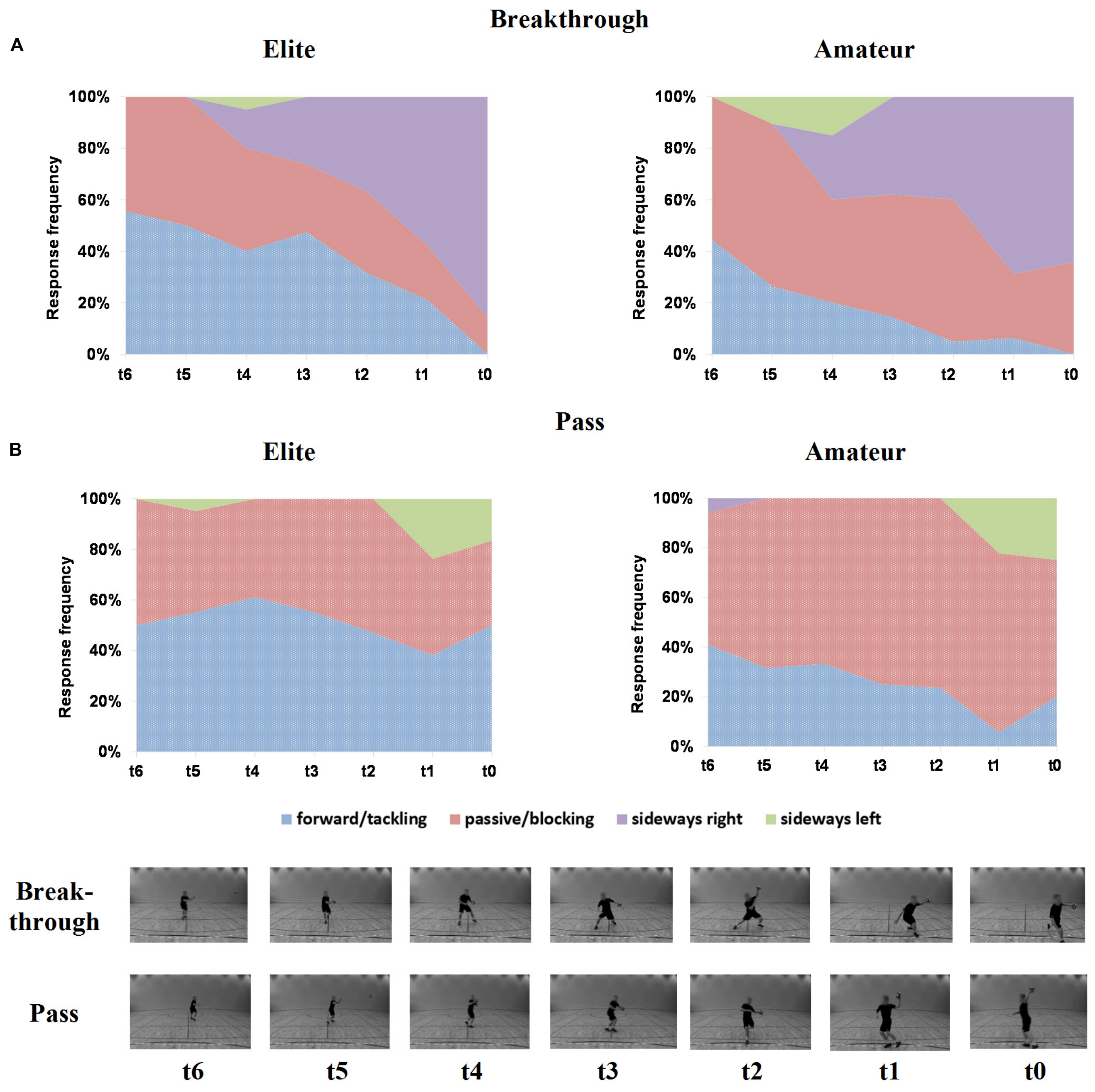

FIGURE 1 | Illustration of significant different frequency distributions of motor responses in left-handed Breakthrough **(A)**, and left-handed Pass **(B)** of elite (left) and amateur players (right). Stacked area graphs show occlusion points (*x*-axis) and (relative) response frequency (*y*-axis). Dotted areas denote significant frequency distribution differences between groups. Screenshots of each video (and its constituent occlusions) are shown at the bottom.

movements in Breakthrough [$\chi^2(14) = 25.06$, $p = 0.033$, OR = 2.76, CI = 1.54–4.95] and Pass [$\chi^2(14) = 37.19$, $p = 0.001$, OR = 3.00, CI = 1.78–5.04]. On the contrary, amateur players instead showed a more frequent use of passive/blocking in Pass [$\chi^2(14) = 28.28$, $p = 0.013$, OR = 2.70, CI = 1.64–4.46] (see **Supplementary Table 2**). Of note, especially regarding single occlusion points with comparably few visual information, elite players use more frequently forward/tackling in Breakthrough [t_3: $\chi^2(1) = 5.20$, $p = 0.023$, $\varphi = -0.36$]. In Jump throw, elite players use more frequently forward/tackling in t_4 [$\chi 2(1) = 4.64$, $p = 0.031$, $\varphi = -0.36$], but switching to more frequent passive/blocking responses at t_3 [$\chi 2(1) = 4.50$, $p = 0.034$, $\varphi = 0.35$]. Another significant between-group difference was observed in Jump throw, where amateur players responded more often with a sideways right move [t_4: $\chi 2(1) = 3.90$, $p = 0.048$, $\varphi = 0.33$] (see **Supplementary Table 2**).

As expected, based on our previous study (Hinz et al., 2021), faster decision times occurred with increasing visual and kinematic information of the attacker in both groups (**Figure 2**). This is evidenced by significant results for the main effect "occlusion" in the repeated measures ANOVA in right-handed [Breakthrough: $F(6, 90) = 4.42$, $p < 0.001$; Jump throw: $F(6, 78) = 10.34$, $p < 0.001$; Standing throw: $F(6, 96) = 9.52$, $p < 0.001$; Pass: $F(6, 96) = 6.51$, $p < 0.001$] and left-handed [Breakthrough: $F(6, 84) = 27.48$, $p < 0.001$; Jump throw: $F(6, 96) = 32.51$, $p < 0.001$; Standing throw: $F(6, 120) = 18.67$, $p < 0.001$; Pass: $F(6, 114) = 17.29$, $p < 0.001$] actions. Between-group comparisons of the main effect "expertise," however, revealed no significant effects. A significant group-by-occlusion [$F(6, 96) = 2.33$, $p < 0.038$] interaction was detected in the right-handed Standing throw. A detailed overview of ANOVA statistics is presented in **Supplementary Table 3**.

DISCUSSION

Considering the need of motor responses in expert decision-making research (Travassos et al., 2013), the current study compared the decision-making behavior between elite and amateur team-handball players, by using sport-specific motor responses in representative near-game test situations. To do so, we measured the frequencies of selected responses, which were given as a team-handball specific defense action on occluded video sequences showing varying attack actions. Additionally, we were interested in the decision time each player required to initialize the respective response selected.

Regarding response frequency, we identified significant effects of expertise in the left-handed Breakthrough and Pass, where elite players demonstrated an overall significant preference to respond with forward/tackling movements on both attack actions. The amateur players, however, preferred to stay rather passive or blocking in Pass. More specifically, preferences for forward/tackling response or passive/blocking responses by the elite players in single occluded time points were also found (at t_4 in left-handed Breakthrough and left-handed Jump throw, and t_3 in left-handed Jump throw). Interestingly, the amateur players demonstrated significant more frequent sideways right responses in the left-handed Jump throw attack. Taken together, the differing frequencies of selected responses from both player groups suggest an expertise-dependent decision-making behavior. Expert effects in our study align with previous motor experiments in decision-making research in team-handball (Raab, 2003; Magnaguagno and Hossner, 2020), and extend them by new insights into how elite and amateur players differ in their tactical understanding of defending when limited visual information is provided.

Regarding decision time, we detected a reciprocal decrease of the time for a decision with increasing kinematic information in the presented attack actions (as found in Hinz et al., 2021). Despite the overall significance of this effect in all of the attacks, an expertise effect in decision time did not appear at all. To the best of our best knowledge, comparable decision (or response) time data from related motor experiments in team-handball using near-game environments do not exist (Bonnet et al., 2020). Previous non-motor experiments (Raab and Laborde, 2011) using offense sequences found expert players to decide better and faster, however, a similar study investigating the influence on mood on decision making found no expertise effect in decision time (Laborde and Raab, 2013). Likewise, the decision time data in our study was also not able to discriminate between groups. The comparability to both of the mentioned studies is to be seen with care, due to the specificity of the offense or defense situations the players were tested in, and due to the methodological aspect of sensorimotor responses in our test instead of verbal reports as responses.

Complex Sensorimotor Decisions Can Distinguish Expertise Levels

In order to classify our findings regarding decision-making behavior, to the best of our knowledge, the virtual reality study of Magnaguagno and Hossner (2020) is one of just a few comparable studies using a sport-specific motor approach to assess defense behavior in team-handball (Magnaguagno and Hossner, 2020; Hinz et al., 2021). Against our approach with four different attack actions in combination with multiple-choice responses, the patterns of play in their video sequences remained stable (lost or won 1 vs. 1 duel of teammate), and response choices were not prespecified. Similar to our expertise effects in decision making, the authors detected significant expert advantages in the correctness of the given motor responses, but response times of the tactical decisions were not regarded, and differentiations of response outcomes regarding handedness of the attacker were also not undertaken. However, the comparability of results from both studies is partially restricted by the assisting role for the participants in the 2 vs. 2 group tactic situation in the Magnaguagno and Hossner study, in contrast to our active 1 vs. 1 situation. Nevertheless, the distinct anticipatory decision-making abilities between experts and near-experts in the mentioned study coincide with our findings of stronger preferences for more offensive-orientated defense actions such as forward movement/tackling of the elite players. The expert players in the Magnaguagno and Hossner study equally demonstrated a significant more frequent tackling behavior.

An interpretation for the evident preferences of elite players for enhanced offensive movements (forward/tackling) in the left-handed attack actions (**Figure 1**) could be that higher performing athletes use kinematic cues in anticipatory processes differently compared to their lower performing counterparts, as stated in research so far (Jackson et al., 2006; Johnston and Morrison, 2016). Put another way, based on the perception of kinematic cues throughout the attackers' movement, elite players could judge this visual information differently, resulting in an altered conversion into a motor response. Another explanatory approach could be found in the impact of the provided context priors to the players (Gredin et al., 2020) in combination with perceived kinematic cues of the attackers' actions. That elite players make different decisions than amateurs might be due to their expert knowledge and experience with the specified defensive tactics, the match status and/or the minute of play. The test instructions

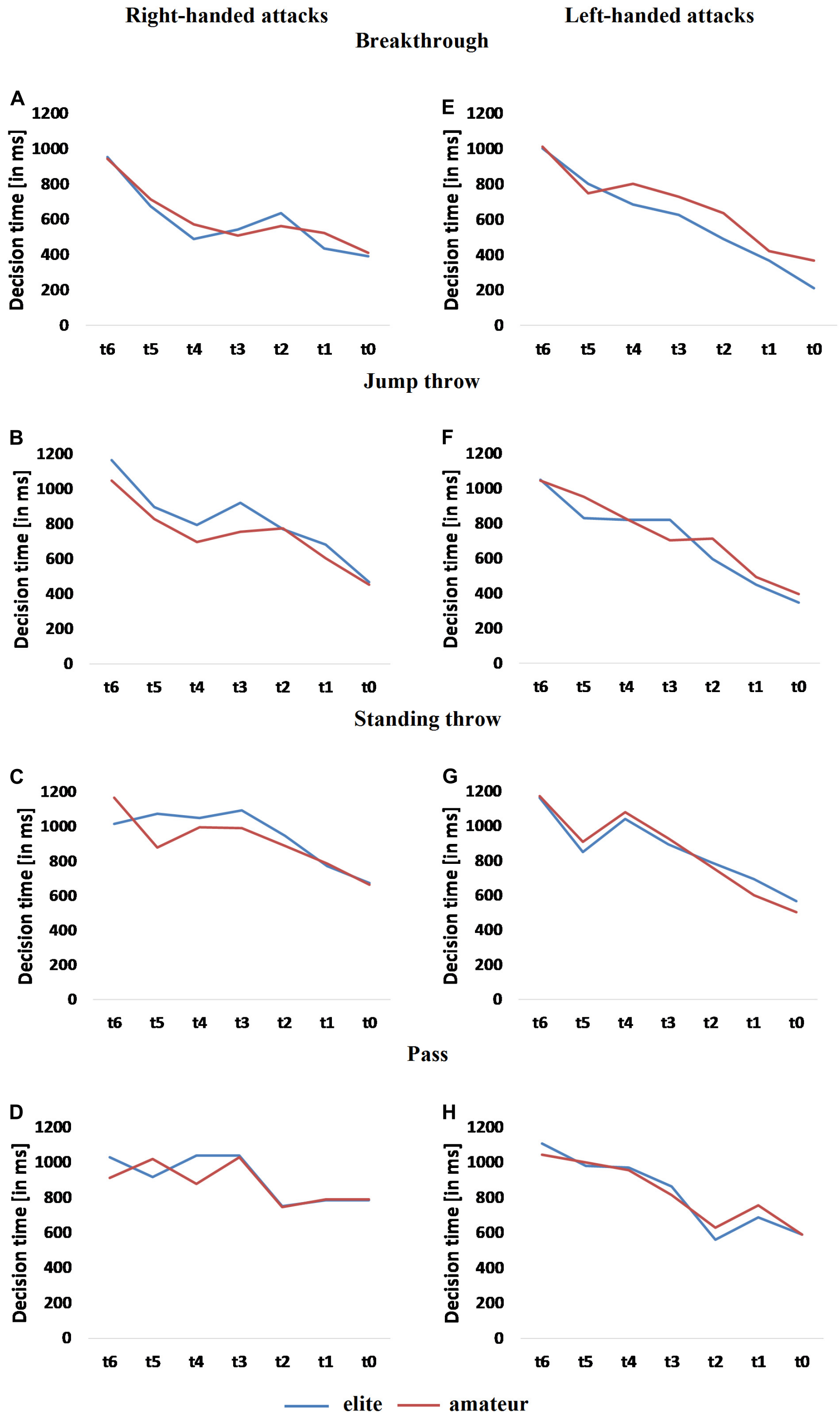

FIGURE 2 | Comparisons of aggregated decision times for all responses between elite and amateur players in right- **(A–D)** and left-handed **(E–H)** attacks.

provided explanations about a man-to-man defense system players, and certain rules within this defense system apply, taught in basic practice lessons from early team-handball ages on Pabst and Scherbaum (2018). With increasing age and expertise level, elite players practice more often and compete higher, therefore learning and adapting defense systems on a higher competition level. We therefore assume that the elite players not only perceive the kinematic information of the attacking players' actions but also taking the increased risk for a wrong decision into account, which is enhanced by the tied game score and the approaching end of the match, subsequently making different tactical decisions than amateur players.

Our study also demonstrated assorted decision-making behavior in right- and left-handed attacks, which transfers the hand-specificity effects from recent embodied choice experiments (van Maarseveen et al., 2018b) into our setting. Previous research on hand-effects in team-handball found evidence for the lack of familiarity with less frequent left-handed opponents (Baker et al., 2013; Loffing et al., 2015), and the dependence on an observers' domain-specific skill to identify the opponent's unfolding action (Loffing et al., 2015). The results obtained from the present study suggest that laterality effects on handball-specific decision making can also be observed in test settings involving motor responses.

Elite Players Invest More Time for Different Decisions

Expectedly, the decision times generally decreased with an increasing amount of visual information as detected in previous team-handball experiments (Raab and Johnson, 2007; Raab and Laborde, 2011; Laborde and Raab, 2013; Loffing et al., 2016; Cocić et al., 2021). Unexpectedly, the non-existent differences in decision time between elite and amateur players are in contrast to previous team-handball studies that determined experts to make better and faster decisions (Raab and Laborde, 2011). It may be assumed that this discrepancy is at least in part related to differences in the experimental setups between studies (e.g., response methods, sample sizes, sub-sample expertise). Providing responses verbally (or *via* keystroke) might yield different outcomes as compared to motor responses in a performer environment setting, as presented in the literature (Ranganathan and Carlton, 2007; Huesmann et al., 2021). At this point, we can only speculate about the reason for this apparent discrepancy.

Considering motor response times in multi-choice tasks (Ratcliff et al., 2016) suggests an increase in insights in cognitive-motor differences between domain-specific expert levels. In their meta-analysis (Travassos et al., 2013), found a moderating effect of requisite responses on decision time in decision-making experiments ($p < 0.001$). A closer inspection on expertise difference for decision time under *in situ* conditions in their analyses revealed non-significant differences between performance level ($p = 0.82$), provided solely by two appropriate studies in the review. Despite the small number of studies, these findings are in agreement with the non-discriminating effect of decision time in our results.

With reference to our complex decision-making setup, and the expertise-related decision-making behavior, we assume that *dynamic inconsistency* mechanisms affect the characteristics of individual decisions in our sample. *Dynamic inconsistency* (Raab, 2003; Raab and Johnson, 2007) explains the tendency to deliberately select a better response option after a first intuitive option that came to an athletes' mind. In this regard, equal decision times might be a consequence of expertise-related top–down (cognitive control of sensory processing) and bottom–up (absence of cognitive control in sensory processing) processes (Raab, 2014) in experts compared to amateurs. We conjecture this deliberate (also considered as corrective) decision-making behavior to be the decisive one that may impact the required time to choose the final decision, and subsequently the decision outcome itself. It can thus be conceivably hypothesized that the perceived kinematic information of the attackers' unfolding action lead to a first intuitive decision preference in both the elite and amateur players (Raab and Laborde, 2011), preparing a motor response tendency toward the attacker (Raab, 2014). But with further kinematic cues in the ongoing time-motion course (occlusions) of the attackers' action, the additional perceived information seem to be judged differently by the elite players compared to the amateur players. The elite players may use recent kinematic information (bottom-up process) for a short-term switch to a more appropriate response, evoked by additional time investments. Such a tendency to switch may depend on accumulated, competitive experiences that equip experts with domain-specific knowledge about situation-specific optimal choices (Raab, 2014, 2020). The suspected corrective and deliberate decisions in elite players in our study differ to some extent from the faster, intuitive decisions of experts in the reported literature (Raab and Johnson, 2007; Raab and Laborde, 2011; Laborde and Raab, 2013). Nevertheless, the comparison of the findings within this context has to be done with care due to the decoupled perception-action responses used in these studies, and the coupled perception-action responses in our study, which could possibly lead to divergent performance outcomes (Farrow et al., 2005; Ranganathan and Carlton, 2007; Huesmann et al., 2021).

Overall, our sport-specific motor approach detected distinctions in decision-making between players of varying performance levels. Hence, future analyses of sensorimotor decision making with take-the-first (Johnson and Raab, 2003) and take-the-best (Gigerenzer and Todd, 2001) heuristic models seem promising.

Limitations and Future Research

We must emphasize that derivations to real-world behavior needs further methodological adjustments in the experimental design.

It still remains open, if the findings obtained in this study reflects the actual on-field behavior of the players. Comparisons of our lab-based performance to the players' on-field performances during a team-handball match would have allowed for further correlations with the data in our study. The players' on-field performances in play could have been captured by using a notational system (expert ratings of players' actions with scores) applied by van Maarseveen et al. (2018a) in soccer. However, a validated team-handball-specific notational system is not existing so far.

Furthermore, players' physical appearance (height, weight), physical skills (speed, agility), and technical skills (high or low level skills, position-specific skills) are performance-discriminating contextual features in team-handball (Wagner et al., 2014) but, for methodological reasons, these features were standardized in the present study. For example, the physical appearance of a backcourt player also affects defense behavior of a central block player, meaning that a taller backcourt player prefers to make advantage of his height by using long distance throws from the backcourt, whereat smaller players rather prefer Breakthrough actions in near-range distance toward the 6 m line. Consequently, there are common tactical approaches to defend taller backcourt players by early tackling them to avoid long rage throws. For this reason, we decided for a standardized test protocol that minimized such contextual features.

Also, intra-individual differences within the expert group itself (elite players) can also affect the obtained performance outcomes, as revealed by the temporal occlusion study of expert field hockey goalkeepers (Morris-Binelli et al., 2021).

Further experimental investigations are needed to address the influence of contextual priors (Gredin et al., 2020) on decision making in representative task designs. Specifically, future studies could integrate stable priors either verbally with coach-like instructions (typical in a match preparation) about action preferences of a special opponent in the stimuli (see Helm et al., 2020; Lüders et al., 2020) or the tactical direction (see Levi and Jackson, 2018). Dynamic priors in terms of a visual response-depending match status (Farrow and Reid, 2012) as feedback would reinforce the pressure condition during the match. Eye-trackers could gain insights about the utilization of kinematic information in the video stimuli in the test (Dicks et al., 2010; Brams et al., 2019).

Due to the qualitative (response frequency) and quantitative (decision time) variables used in this study, T-pattern analyses, a software-based mixed methods approach, could give additional enlightenment about the temporal structure of the player's decision behavior (Magnusson, 2000). T-patterns are dendrograms, showing the order and the temporal distributions of occurrences, as well as recurring series of behavioral occurrences. In other words: "if A is an earlier and B a later component of the same recurring T-pattern, then, after an occurrence of A at *t*, there is an interval that tends to contain at least one occurrence of B more often than would be expected by chance" (Magnusson, 2000). Pic (2018) found more T-patterns in home teams compared to away teams in team-handball, meaning that home teams showed repeating patterns of throws in the left and right areas toward the opponent goalkeeper with greater chances for success. Future analyses with this method could explain strategic details and the temporal distributions in defensive decision-making processes, such as repeating slower but better defense responses on specific attack actions.

To conclude, there is accumulating evidence that perceptual-cognitive skills such as decision making constitute a performance-discriminating component in team-sports. The observed expertise effect in response frequency indicates preferences for forward/tackling responses of elite players. Our results are also indicative of *dynamic inconsistency* mechanisms from simple heuristics literature (Raab, 2003; Raab and Johnson, 2007; Raab and Laborde, 2011). Thus, a non-existent expertise effect in decision time may suggest that the required time for making a decision could play a more important role in decision making and simple heuristics than previously assumed. Taken together, our findings serve recent calls in sport science for an enhanced utilization of multidisciplinary test approaches when assessing complex sportive behavior of athletes. Talent detection and identification processes should henceforth apply sport-specific performance tests which take the perceptual-cognitive capabilities of athletes into account. Considering decision making in performance analyses could provide a more holistic estimate of an athletes' talent and performance potential, as a product of the athletes' sensory and biomotor capacities at the same time.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Local Ethics Committee from the Otto von Guericke University Magdeburg. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

MT, KM, and MH: conceptualization. NL, MT, and MH: methodology and validation. MH: software, investigation, resources, data curation, and writing – original draft preparation. NL and MH: formal analysis and visualization. MT, HW, NA, JT-C, and NL: writing – review and editing. MT and HW: supervision. MT and KM: project administration and funding acquisition. All authors have read and agreed to the published version of the manuscript.

FUNDING

This work was supported by the Federal Institute of Sport Science (IIA1-70506/19-20). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

ACKNOWLEDGMENTS

We want to thank Kolya Laade for the programming of all test scenarios, Nico Richter, and Johannes Riedel for the data collection, as well as Jeremy King for English proofreading. We also thank all players of the SC Magdeburg and the local team-handball clubs for their participation in this study. We acknowledge support for the Book Processing Charge by the Open Access Publication Fund of Magdeburg University.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.854208/full#supplementary-material

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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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ORIGINAL RESEARCH
published: 12 April 2022
doi: 10.3389/fpsyg.2022.799316

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Effects of Age and Expertise on Mental Representation of the Throwing Movement Among 6- to 16-Year-Olds

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OPEN ACCESS

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

Received: *21 October 2021*
Accepted: *14 February 2022*
Published: *12 April 2022*

Citation:
Gromeier M, Schack T and Koester D (2022) Effects of Age and Expertise on Mental Representation of the Throwing Movement Among 6- to 16-Year-Olds. Front. Psychol. 13:799316. doi: 10.3389/fpsyg.2022.799316

The aim of this article was to assess the development of mental representation of the overhead throwing movement as a function of age and expertise. The mental representational structure of the overhead throwing movement was measured using the Structural Dimensional Analysis-Motoric (SDA-M) method that reflects the organization of basic action concepts (BACs). BACs are fundamental building blocks of mental representations, which comprise functional, sensory, spatiotemporal, and biomechanical characteristics of a movement (Schack, 2010). In this study, novices and handball athletes (N = 199) each were grouped according to the level of development in motor ontogenesis (in childhood, pubescence, and adolescents). Male and female handball athletes played in the highest leagues of their age groups. As a result, novices of all age groups showed the same unstructured mental representation. Athletes in the earliest age band resemble all novices' groups and showed similar unstructured mental representation, whereas athletes within pubescence and adolescents showed functionally well-structured representations, which were similar to the structure of the reference group (N = 8). These results are consistent with a previous investigation of related quantitative and qualitative performance parameters of the overhead throwing movement (Gromeier et al., 2017). Without an increased training, neither the throwing performance nor the associated mental representation is unlikely to improve further by itself or automatically.

Keywords: mental representation, SDA-M, motor skill development, movement expertise, throwing movement, overarm throwing motion, cognitive performance

INTRODUCTION

The overhead throwing movement is a complex and basic motor skill and a fundamental requirement for a number of sports, such as handball, baseball, and javelin. Typical handball-specific situations in which the overarm throwing movement comes into effect are 7 m throws, free throws, backcourt throws, and the initiation of fast breaks (Kolodziej, 2010). This motor skill is an important part of school and university education, as well as belonging to the club sport. The overhead throwing movement is a highly demanding coordinative skill, and it is said to be "one of the most difficult fundamental motor skill[s] for children and adults and its acquisition requires coordination of the whole body" (Hamilton and Tate, 2002, p. 49). During learning of complex motor skills, children and adolescents are repeatedly confronted with excessive demands of coordination. Due to the complexity of the overhead throwing movement, difficulties in movement performance can often be observed in exercises and game situations (e.g., physical education, university education, or club sports).

The Overhead Throwing Movement

A large number of studies have examined expertise and gender-related differences in the overhead throwing movement in different handball and throwing situations (e.g., Hicks, 1931; Wild, 1938; van den Tillaar and Ettema, 2004; Laffaye et al., 2012; Karadenizlil et al., 2014; Rousanoglou et al., 2015; Maselli et al., 2019) and a variety of disciplines (Lombardo and Deaner, 2018). Significant differences in throwing velocity and throwing range were mainly demonstrated in favor of men (Keogh, 1969; Morris et al., 1982; Thomas and French, 1985; Geese, 1997; Roberton and Konczak, 2001; Zhu et al., 2009). Other studies recognized differences in throwing accuracy (Keogh, 1969; Vogt, 1978; Thomas and French, 1985; Geese, 1997; Gaschler, 1998; Ahnert, 2005) and in the qualitative characteristics of overhead throwing movements and typically, were also in favor of men compared with women (Keogh, 1969; Vogt, 1978; Thomas and French, 1985; Nelson et al., 1991; Geese, 1997; Gaschler, 1998; Ahnert, 2005; but see Gromeier et al., 2017).

Differences among novices, beginners, advanced, and experts were unambiguously demonstrated in throwing velocity and throwing accuracy (e.g., van den Tillaar and Ettema, 2004; Gorostiaga et al., 2005; Rivilla-García et al., 2010; Rousanoglou et al., 2015).

The studies of Gorostiaga et al. (2005) clarify quantitative differences between two handball male teams, namely, expert team, one of the world's leading teams, and amateur team, playing in the Spanish National Second Division. Experts showed significantly higher velocity of throwing without stepping and three-step rhythm than amateurs using the same approach. Rousanoglou et al. (2015) found similar results when comparing between experts and amateurs. Amateurs performed with significantly lower values in velocity of throwing and worse throwing accuracy. Rivilla-García et al. (2010) found significant differences in velocity between senior players and U-18 players in different throwing situations. Senior players were found to perform significantly better than the U-18 players in all four throwing situations. The quantitative characteristics of throwing movements of experts and beginners in handball were also analyzed by van den Tillaar and Ettema (2004). They evaluated Norwegian handball players at the age of 20–24 years and found gender differences in the throwing velocity in favor of men compared with women.

In previous investigations, differences in quantitative and qualitative throwing performances of novices and athletes across a life span of 6–16 years of age were examined (Gromeier et al., 2017, 2019). It was shown that novices during childhood, pubescence, and adolescents and athletes in childhood have similar results in throwing performance of the overhead throwing movement. These results are different to the athletes in pubescence and adolescents. Among the athletes, a developmental spurt between the stage of childhood and the pubescence can be assumed. This is suggested by the significant improvements in the quantitative and qualitative movement performances. This confirms the results of Rivilla-García et al. (2010), Laffaye et al. (2012) and Rousanoglou et al. (2015), who showed that amateurs have significantly worse quantitative performance in throwing accuracy than expert players. The specific training among the athletes apparently leads to increasing quantitative and qualitative throwing performances. The outcome of novices differs drastically. No reliable improvement was observed among the novices. Throughout the 10-year period, novices did not increase their quantitative performance or their qualitative performance. These results contradict the studies by Roberton and Langendorfer (1980), Halverson et al. (1982), Roberton and Konczak (2001), and Goodway and Lorson (2008), who found age-related developments in throwing performances. Most of our fundamental motor skills, like overhead throwing movements are naturally acquired, as children play and move around by themselves. The innate motor and perceptual capabilities provide a basis for the acquisition of these patterns (Barela, 2013; Gromeier et al., 2017). The overarm throwing movement is a complex movement with a specific and clearly identifiable start and end. The movement can be divided into distinct phases (Werner et al., 1993). This type of throwing movement seems to follow a specific movement pattern determined by a proximal to distal sequence of segments. According to Wagner et al. (2014, p. 345), the "equal order of the proximal-to-distal sequencing and similar angles in the acceleration phase suggests there is a general motor pattern in overarm movements." Also, and more importantly, there are specific and typically mistakes in the performance of the throwing movement characteristics including, stepping, backswing, humerus oblique under shoulder, no stepping, backswing, and trunk forward-flexion (Roberton and Langendorfer, 1980; Halverson et al., 1982; Roberton and Konczak, 2001; Goodway and Lorson, 2008; Gromeier et al., 2017).

The way of how these moving patterns will change over the time depends on training intervention, learning, and adaptation that will arise through perceptual-motor experiences that children would have during childhood (Barela, 2013; Gromeier et al., 2017, 2019). These results suggest that most of children and adolescents do not master skill performance and would not acquire the most proficient performance in the fundamental motor skills, like overhead throwing movements (Gallahue, 1982). The performance requirements for overhead throwing movement execution may be representing a natural limitation, caused among other things by the change in the living world. The difficulties in the performance of overhead throwing movement could be a possible hint of a motor skill "proficiency barrier" (Seefeldt, 1980). Gallahue (1982) argued that fundamental motor skills would require regular physical education, composed by structured practice, specialist teachers, and specific conditions, and promote gross motor development of children.

Developmental Psychology in Youth Sport

Based on Piaget's (1950) model of cognitive development and Erikson's (1950) stages of psychosocial development, there are distinct developmental phases. In accordance with Piaget (1950) and Erikson (1950), Meinel and Schnabel (1998) described a phased development of movements and interpreted the respective stages of development as integration at a higher level of performance. Covering the entire life span, Meinel and Schnabel (1998) focused exclusively on sports motor aspects, which are similar to the development model of Gallahue et al. (2012). Gallahue et al. (2012) and Meinel and Schnabel (1998) focused on the phases of motor development and provided a solid introduction to the biological, affective, cognitive, and behavioral aspects within each developmental stage and differed mainly in the temporal organization of developmental stages.

However, there is likely to be certain variation in the physical, cognitive, social, and emotional development within each developmental stages, and each child develops at her or his own natural speed, and variety of motor and cognitive development is shown to proceed in a specific, predictable sequence, and a number of features of normal motor and cognitive development can be distinguished and improved as the children's ages increased. The findings of De Waelle et al. (2021) indicate that age-related improvements of perceptual-cognitive skills are evident. The authors examined the development of anticipation, decision-making, and pattern recall in female volleyball players of six different age groups and find out that adolescents and adult athletes had superior accuracy and shorter response times than younger athletes. A study by Caeyenberghs et al. (2009) shows age-related changes of motor imagery in children using a cross-sectional design, with significant improvements of motor imagery occurring after 7–8 years of age. Related to comparable age bands, these results were underlined by Souto et al. (2020) who found out that motor imagery ability improved as a function of age. Overall, phases of motor and cognitive development can be seen as general guide to cognitive development and as sources of constraints on what structures and functions are available to the developing mind (Feldman, 2004).

Mental representations play a central role in the control and organization of action. Complex actions are believed to consist of hierarchical taxonomies comprising basic action concepts (BACs). BACs are cognitive clusters of (anticipated) movement effects and, therefore, contain integrated feature-based units that represent functional, sensory and spatiotemporal, and biomechanical characteristics of a movement (Schack, 2010). BACs combine functional movement features and provide the representational basis for the control of complex actions (Schack, 2004; Schack and Mechsner, 2006; Bläsing et al., 2009). Motor learning, and more precisely, learning by repeated execution of complex action, is reflected by functional changes in the relations and the groupings of BACs (e.g., Schack and Mechsner, 2006; Schack and Ritter, 2013). Consequently, motor performance becomes optimized, which may lead to automaticity of movement execution. Thus, well-structured patterns in mental representation are essential for the movement control (Schack, 2010). The storage of mental representation of overhead throwing movements can be evaluated using the Structural Dimension Analysis-Motoric (SDA-M; Schack, 2004). The SDA-M was developed based on the approach of the cognitive architecture of human motion (Lander and Lange, 1996; Schack, 2004, 2012). The SDA-M is a measuring method that objectifies the mental representations of movements and their internal structure in long-term memory by a successive splitting procedure (Schack, 2012).

Studies demonstrate that well-trained athletes and experts in various sports can be characterized by well-structured patterns of perceptual cognitive concepts, which is reflecting the functional phases of the motor skills. In contrast, novices show usually unstructured patterns in mental representation of motor skills (e.g., Schack and Mechsner, 2006; Bläsing et al., 2009; Stoeckel and Wang, 2011) and at early phases of the learning process of motor skills (e.g., Frank et al., 2016). Stoeckel and Wang (2011) analyzed the anticipatory motor planning and the development of mental representation of grasp posture of children. School children aged 7, 8, and 9 years participated in that study (Stoeckel and Wang, 2011). The mental representation was evaluated using a splitting procedure. The children successively judged the similarity of pictures depicting an object that was grasped in a comfortable or uncomfortable manner. The results highlight that 9-year-old children show clear cluster solutions in the representation structure. They distinguished uncomfortable grasp postures from comfortable grasp postures. The mental representations of 7- and 8-year-old children were not clearly structured in uncomfortable grasp postures and comfortable grasp postures. These results highlight the development of mental representation of motor skills during childhood as a function of age.

Among the key issue is how structured mental representations can arise during motor skill acquisition in throwing in schools and club sports. This study analyzed mental representations of overhead throwing movement among 6- to 16-year-olds to find out whether an overhead throwing movement improvement is accompanied by cognitive improvement.

The aim of this study was to examine the mental representation of the overhead throwing movement of different age groups and expertise. We expected that a growing expertise's improvement in quantitative and qualitative throwing performance is accompanied by an improvement of the mental representation (Frank et al., 2016). Among athletes, it is hypothesized that with an increasing training level, children would distinguish technically correct and technically faulty clusters of movement representations. Moreover, at a certain level, athletes are expected to show similar cluster solutions in line with the reference representation structure. It is also hypothesized that novices distinguish technically correct and technically faulty BACs with an increasing age, but compared with athletes, they show less growth. Thus, we predict that the mental representation of overhead throwing movements would develop as a function of age concerning novices and as a function of expertise concerning athletes (Stoeckel and Wang, 2011; Frank et al., 2013, 2014, 2016).

MATERIALS AND METHODS

Participants

A total of 206 participants, aged between 6 and 16 years (M_{age} = 11.31 years; SD_{age} = 2.989), 89 women and 117 men, took part in the study. The group of athletes (N = 96, M_{age} = 11.93 years; SD_{age} = 3.190) consisted of 37 female and 59 male subjects. All of these experts played active handball in the highest league of their age group. The sport clubs of these teams have a competitive sport orientation with a greater exercise frequency and intensity, thus enhancing practice and training. Moreover, athletes with competitive sport orientation often are highly motivated and trying to seek achievements in sport. The group of novices (N = 110, M_{age} = 10.76 years; SD_{age} = 2.702) consisted of 52 women and 58 men and came from public comprehensive schools. These participants had no prior experience in sports such as handball, baseball, tennis, volleyball or track, and field neither in club sports nor leisure groups. Thus, movement experiences in throwing and throwing skills have mainly developed by the private sports in the family, leisure time, and school education. Children and adolescents that have been active in other sports (e.g., dancing, gymnastics, martial arts, and swimming) were included in the group of novices.

The cluster solutions of the tested subjects were compared with those of reference group (RG), which consisted of eight experts (M_{age} = 18 years; SD = 0.000), four women and four men. They were playing in the national handball Bundesliga-A-juniors and were partly in an enlarged cadre of senior Bundesliga-team (mean age of the training = 11.5 years, training frequency per week = 12.5 h). The investigated movement is highly relevant for throwing in handball athletes. In line with the study by Wiener (2011), it is said that typical handball-specific situations in which the overarm throwing movement comes into effect are 7 m throws, free throws, backcourt throws, and the initiation of fast breaks. Because of repetitive throwing movements in game and training situations, it is suggested that the overhead throwing movement is well established in motor skills of athletes. From a functional perspective, the main function phase is directly related to the main movement goal, and it is identical to main functional phase of various kinds of throwing, which are used in real-game situations, e.g., jump throw or throwing with run-up (Göhner, 1979). Therefore, the training concept of the German Handball Association provides binding guidelines regarding the use the overhead throwing movement in 7-m throws (DHB, 2013). Due to repetitive throwing movements in game and training situations, it is suggested that the overhead throwing movement is well established in motor skills of athletes. To take part in the experiment, the parents of the participants gave informed consent. Throughout the motor testing, all participants were healthy and in good condition. The study was performed in accordance with the ethical standards of the Declaration of Helsinki 1975 (World Medical Association [WMA], 2013). Our study was also approved by the ethics committee ("Ethik-Kommission") at Bielefeld University and adhered to the ethical standards of the latest revision of the Declaration of Helsinki. For the data analysis, we grouped three age groups for two different skill levels according to the level of development in motor ontogenesis of Meinel and Schnabel (1998) (i.e., childhood, up to 12 years, N = 75 novices and N = 45 athletes; pubescence, above 12–14 years, N = 17 novices and N = 24 athletes; and adolescents, above 14–16 years, N = 18 novices and N = 20 athletes).

Mental Representation Structure of the Overhead Throwing Movement

Apparatus and Stimulus

The stimuli were 10 pictures of the overhead throwing movement representing the respective BACs (see **Table 1**). Based on a pilot study with 15 students and expert's surveys with two former national handball athletes, five of the BACs were always categorized as showing technically correct movements, and in contrast, five were categorized as showing technically faulty movements. Therefore, the pictures (BACs) can be divided into two categories. The faulty BACs showed common main faults in the movement, which have been described and proven by many authors (e.g. Roberton and Konczak, 2001; van den Tillaar and Ettema, 2004; Ahnert, 2005; Goodway and Lorson, 2008; Gromeier et al., 2017, 2019). The correct BAC in the other category showed the correct movement execution.

The stimuli had a size of 9.0 cm × 9.0 cm (250 × 250 pixels) and were shown on a laptop (Sony Vaio). The participants sat approximately 50 cm away from a 15-inch laptop screen.

Task and Procedure

The mental representation was assessed using the SDA-M (Schack, 2004). For this, we determined the distances of the mental link of all relevant BACs by a splitting technique. The participants replied verbally and judged the similarity of the BACs with one another. Therefore, each picture (N = 10) was presented as an anchor. This anchor was displayed in the upper half of the screen. The remaining pictures were successively displayed below them and were classified to the anchor picture as similar or not similar. The participants were individually tested in a separate room, without any time pressure. Depending on the age of the participants, the testing took up to 25 min. The participants could cancel the experiment at any time without having to provide reason.

The participants were instructed to classify from their own perception, whether the two pictures shown at the laptop screen were similar or not. In case of similarity, both depicted movements should be perceived as fluent and pleasant respectively comfortable, and they show an appropriate solution of the movement goal. Or both depicted movements should be perceived as non-fluent and unpleasant respectively uncomfortable, and they show an inappropriate solution of the movement goal (Stoeckel et al., 2012). If the pictures did not correspond, they were classified as dissimilar. According to this question, it was found out that in the RG, the technically correct pictures could be characterized as a clearly comfortable. In contrast, the faulty patterns for the RG are seen as explicitly uncomfortable (see **Figure 2**). The group analysis of the RG clarified a definite assignment of technically correct and technically faulty BACs, separated into clusters.

Especially among the younger participants, it was necessary to explain the task clearly and understandably. For this matter, the test started with the following text (translation of German original):

During the motor test you had thrown at a target with a ball. And maybe you remember games or situations in which you have thrown a ball or a snowball for example. I'll show you some pictures. On these pictures you can see a person, named Yannik throwing a ball, like you did. Yannik threw in two different ways. Sometimes he threw in a comfortable manner, and sometimes he threw in an uncomfortable manner. I want you to tell me, whether both displayed movements are comfortable or uncomfortable, or whether one displayed movement is comfortable and the other displayed movement is uncomfortable.

Data Analysis

The experimental procedure of the SDA-M includes four steps. In the first step of the SDA-M, the distance between all images (i.e., BACs) by a multiple sorting task was analyzed. In a pairwise comparison, the participants assessed the similarity of all BACs with one another. In this splitting procedure, each concept was displayed as an anchor concept on a computer screen. Any remaining concepts were compared with that anchor successively. The participants were to decide whether the displayed concepts were related to each other. All concepts were compared with all other concepts. In the second step, the individual cluster solutions were formed by means of a hierarchical cluster analysis. As a result, an individual cluster with ten decision trees was formed and was depicted as a dendrogram (see **Figure 2**). Based on a significance level of $p = 0.05$, a Euclidean distance ($d_{\text{crit}} = 3.41$) was defined (cf. Schack, 2012, 2004). All connection points below the Euclidean distance d_{crit} were viewed as not significantly associated, while the connections points above Euclidean distance d_{crit} were viewed as significantly associated. In this study, an optimal dendrogram shows a two-cluster solution (Schack, 2012, p. 206); one cluster with technically correct BACs and one cluster with technically faulty BACs. The third step contains the measurement of invariance of cluster solutions within and between groups. In a final step, the authors assessed the structural invariance within and between group cluster solutions by means of an invariance measure (λ). The final comparison of λ with $\lambda_{\text{crit}} = 0.68$ makes statements about the manner in which the cluster solutions have significantly similar structure to a predefined reference ($\lambda_{ideal} = 1$). This means that there was a significant difference between clusters if $\lambda < \lambda_{\text{crit}} = 0.68$. If λ is greater than λ_{crit}, there is a significant similarity, which corresponds to an alpha level of 5% (Schack, 2012). The Rand Index was used to compare the differences of the representation structure of age and gender groups.

The cluster analysis (**Figure 1**) shows the group structure of the RG, which represents the optimal cluster solution of the SDA-M. The horizontal dashed line indicates the critical value ($d_{\text{crit}} = 3.51$). The dendrogram of the RG shows a clear separation in technically correct (pictures 1–5) and faulty BACs (pictures 6–10). The hubs are highly interconnected and are clearly below the critical distance ($d_{\text{crit}} = 3.51$). Within the RG, it is possible to determine a definite structure by a significant separation in technically correct BACs underlined with a gray solid bar and faulty BACs underlined with a diagonally striped bar. If the value is $\lambda_{\text{crit}} = 0.68$ is reached or exceeded, the cluster solutions are invariant. Within the RG, the λ-values were between 0.71 and 1.00. Therefore, within the reference, the individual cluster solutions are identical.

RESULTS

Figures 2–7 illustrate the average cognitive representation structure of all age groups and the level of expertise displayed as dendrograms. The BACs (pictures 1–5) marked with a gray solid bar are related to technically correct movements, and BACs (pictures 6–10) marked with a diagonally striped bar are related to technical faulty movements (pictures 6–10).

Within-Group Comparison Novices Within Childhood

Within childhood, the group of novices (see **Figure 2**) shows four clusters in their representation structure. They clustered two technically correct (pictures 1 and 2; pictures 3–5) and two faulty (pictures 7–9; pictures 6 and 10) solutions.

Within-Group Comparison of Novices Within Pubescence

In the cluster solution of novices within pubescence (see **Figure 3**), three clusters can be seen. In contrast to childhood, one technically correct cluster solution (pictures 1 and 2), one faulty solution (pictures 6, 8, and 10), and one mixed consisting of a correct and faulty solution (pictures 3, 5, 4, 7, and 9) were formed by novices. They could not separate the technically correct and faulty concepts from each other.

Within-Group Comparison of Novices Within Adolescents

The cluster solution of novices within adolescents (see **Figure 4**) shows a similar structure to the novices within childhood. They indicate four clusters, two technically correct (pictures 1, 2, and 4; pictures 3 and 5) and two technically faulty (pictures 7, 9, and 8; pictures 6 and 10) solutions.

Within-Group Comparison of Athletes Within Childhood

A similar cluster solution to the novice group within childhood is shown by athlete within childhood (**Figure 5**). They also separate two technical correct (pictures 1 and 2; pictures 3, 4, and 5) and two faulty (pictures 7, 9, and 8; pictures 6 and 10) clusters in their representation structure. For all four groups, the nodes are located slightly below the critical distance ($d_{\text{crit}} = 3.51$, $p = 5\%$) and are only faintly connected to each other.

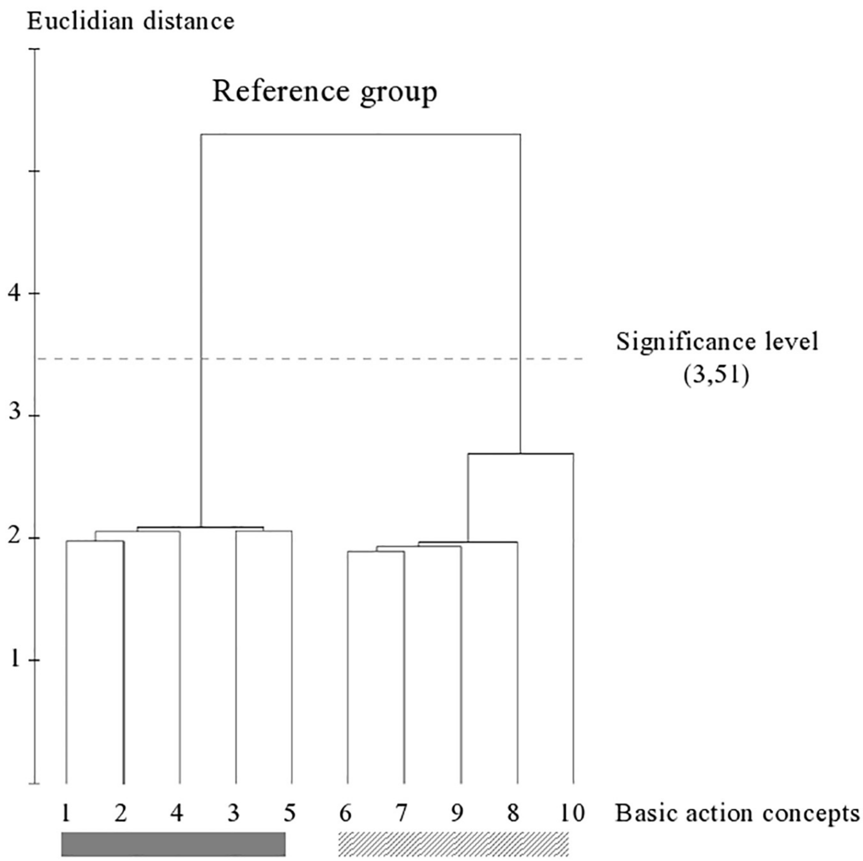


FIGURE 1 | Outcome of the hierarchical cluster analysis for the reference group (N = 8, M_{age} = 18 years) displayed as a dendrogram (p = 5%; d_{crit} = 3.51). The basic action concepts (BACs) are marked with numbers below the dendrogram. The resulting clusters are highlighted with the gray solid bar (pictures 1–5, technically correct BACs) and diagonally striped bar (pictures 6–10, faulty BACs).

Group of Athletes Within Pubescence and Adolescents

The cluster analysis (refer to **Figures 6**, **7**) shows the representation structure for athletes in pubescence and adolescents. Their dendrograms clarify identical cluster solutions and show a clear separation in technically correct (pictures 1–5) and faulty BACs (pictures 6–10) as the RG. The hubs are highly interconnected and are clearly below the critical distance (d_{crit} = 3.51).

Between-Group Comparisons

The invariance analysis indicates that the representation structures of overhead throwing movement were identical (λ = 1; λ_{crit} = 0.68) among these groups (refer to **Table 2**). The results highlighted that the novices in adolescents were at the level of the athletes within childhood. **Table 2** clarifies that the representation structure for all age groups of novices and the athletes within childhood show no similarity (λ = 0.59; λ_{crit} = 0.68) with the representation structure of athletes in pubescence and adolescents. The cluster solutions also differ (λ = 0.59; λ_{crit} = 0.68) from the cluster solution of the RG, too (see **Table 2**). The dendrograms for athletes in pubescence and adolescents clarify identical cluster solutions as the RG. These cluster solutions match to RG (λ = 1; λ_{crit} = 0.68). Both group cluster solutions show two clusters and a clear separation in a technically correct (pictures 1–5) and faulty concepts (pictures 6–10). Similar to the RG, the nodes are highly interconnected and below the critical distance (d_{crit} = 3.51).

DISCUSSION

The aim of this study was to explore age- and expertise-related differences in mental representation of the overhead throwing movement. The SDA-M (Schack, 2010) was used to analyze the mental representation.

All novices, children, pubescence, and adolescents showed the same unstructured mental representation, and there were no differences in the quality of the mental representation of the overhead throwing movement characteristics between the various levels of development in motor ontogenesis. All age groups could not distinguish the technically correct and faulty concepts from each other. Thus, the mental representation of overhead throwing movements did not develop as a function of age until adolescents. It is remarkable that children from 6 to

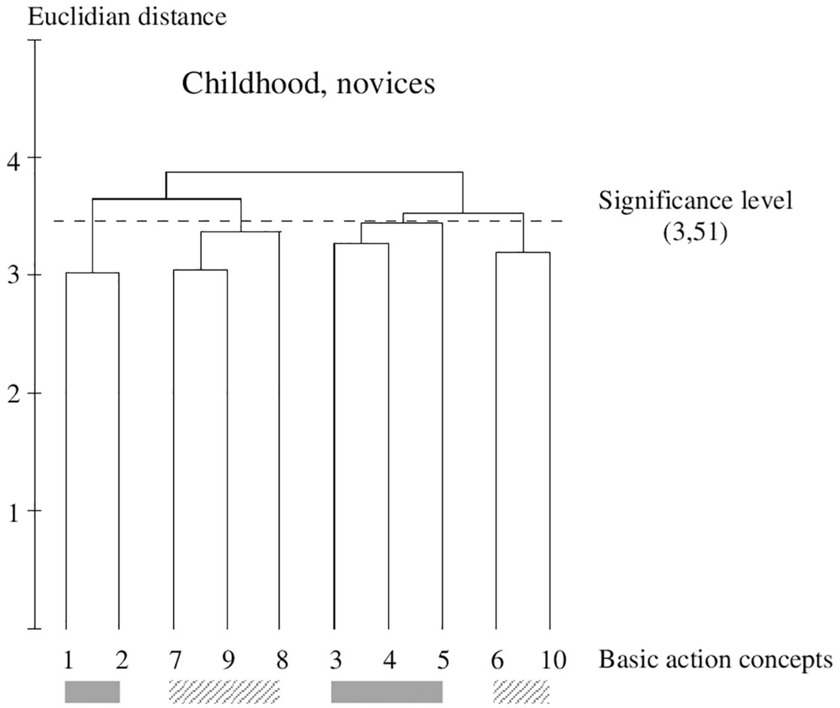


FIGURE 2 | Outcome of the hierarchical cluster analysis of novices within childhood (*N* = 75) displayed as a dendrogram. The dashed line clarifies the critical value of d_{crit} = 3.51, which corresponds to a significance level of 5%. The BACs are marked with numbers among the dendrogram and highlighted with the gray solid bar (technically correct BAC) and diagonally striped bar (faulty BAC).

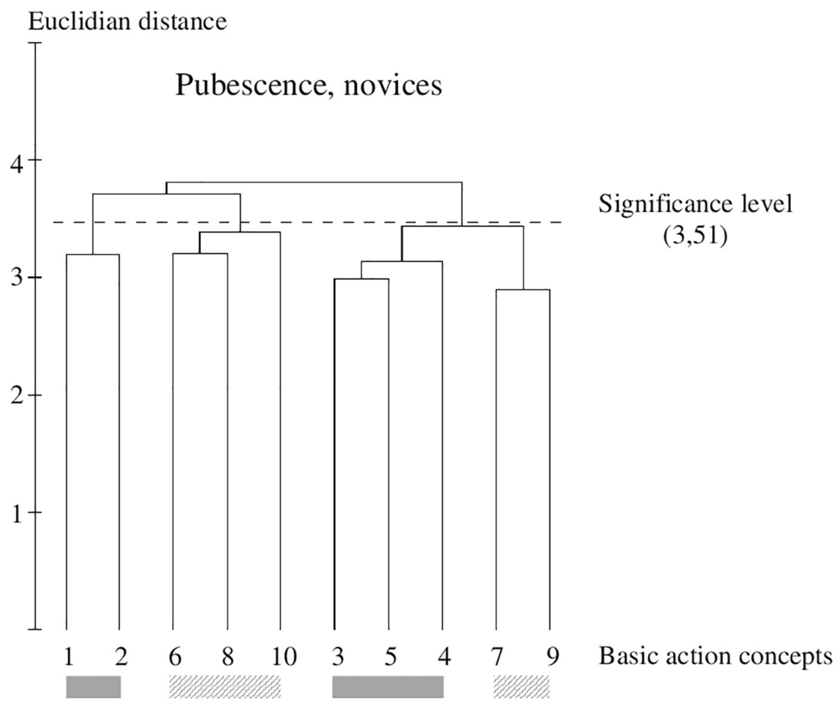


FIGURE 3 | Outcome of the hierarchical cluster analysis of novices within pubescence (*N* = 17) displayed as a dendrogram. The dashed line clarifies the critical value of d_{crit} = 3.51, which corresponds to a significance level of 5%. The BACs are marked with numbers among dendrogram and highlighted with the gray solid bar (technically correct BAC) and diagonally striped bar (faulty BAC).

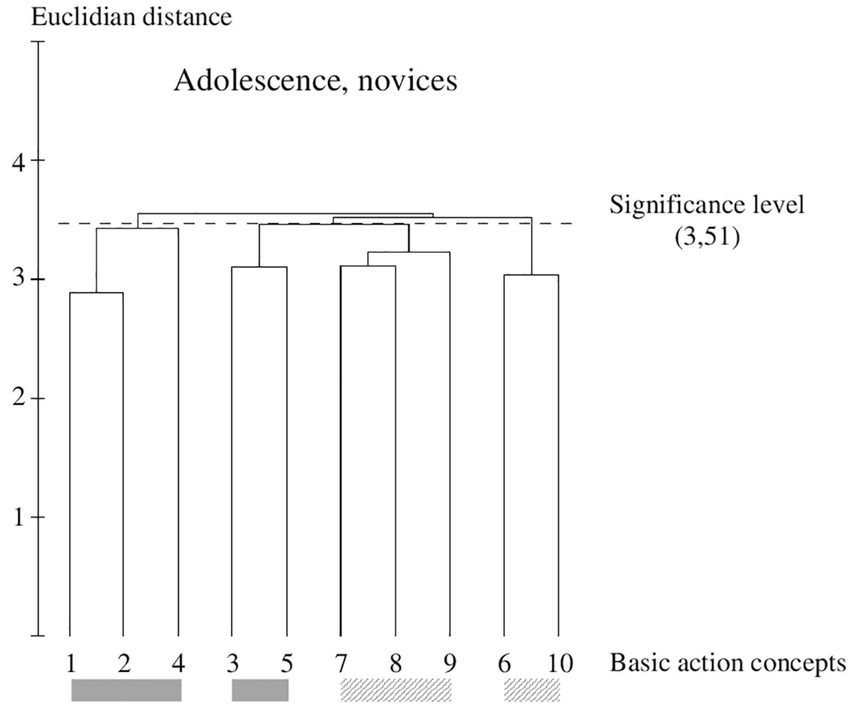


FIGURE 4 | Outcome of the hierarchical cluster analysis of novices within adolescents (N = 18) displayed as a dendrogram. The dashed line clarifies the critical value of d_{crit} = 3.51, which corresponds to a significance level of 5%. The BACs are marked with numbers among the dendrogram and highlighted with the gray solid bar (technically correct BAC) and diagonally striped bar (faulty BAC).

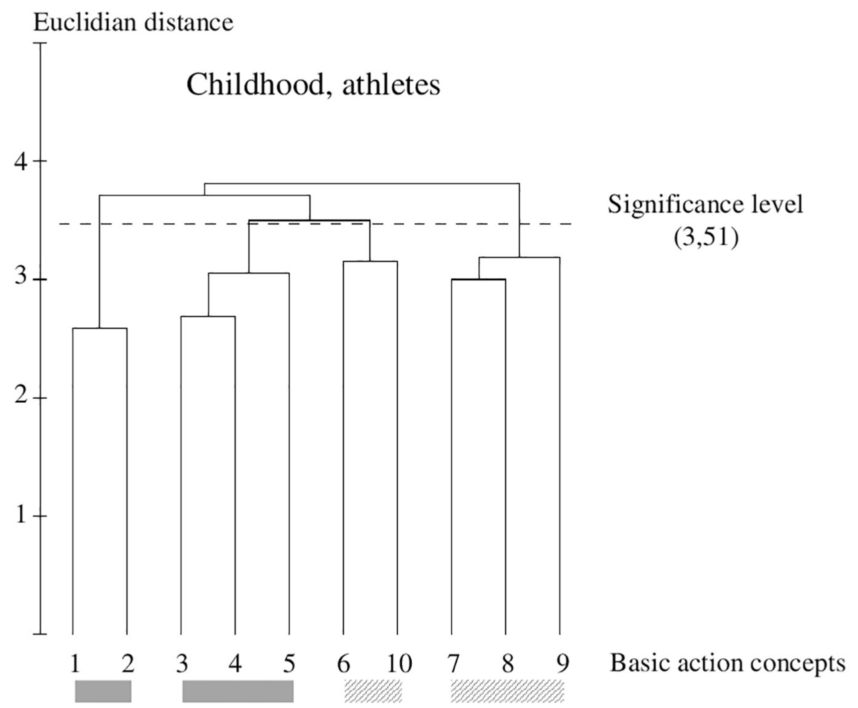


FIGURE 5 | Outcome of the hierarchical cluster analysis of athletes within childhood (N = 45) displayed as a dendrogram. The dashed line clarifies the critical value of d_{crit} = 3.51, which corresponds to a significance level of 5%. The BACs are marked with numbers among a dendrogram and highlighted with the gray solid bar (technically correct BAC) and diagonally striped bar (faulty BAC).

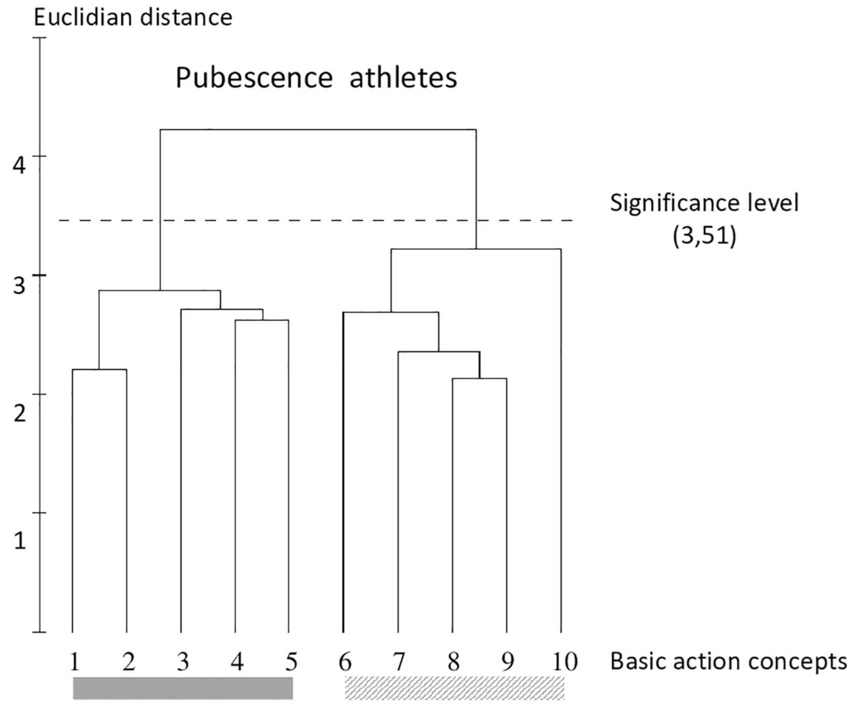


FIGURE 6 | Outcome of the hierarchical cluster analysis of athletes within pubescence (N = 24) displayed as a dendrogram. The dashed line clarifies the critical value of d_{crit} = 3.51, which corresponds to a significance level of 5%. The BACs are marked with numbers among the dendrogram and highlighted with the gray solid bar (technically correct BAC) and diagonally striped bar (faulty BAC).

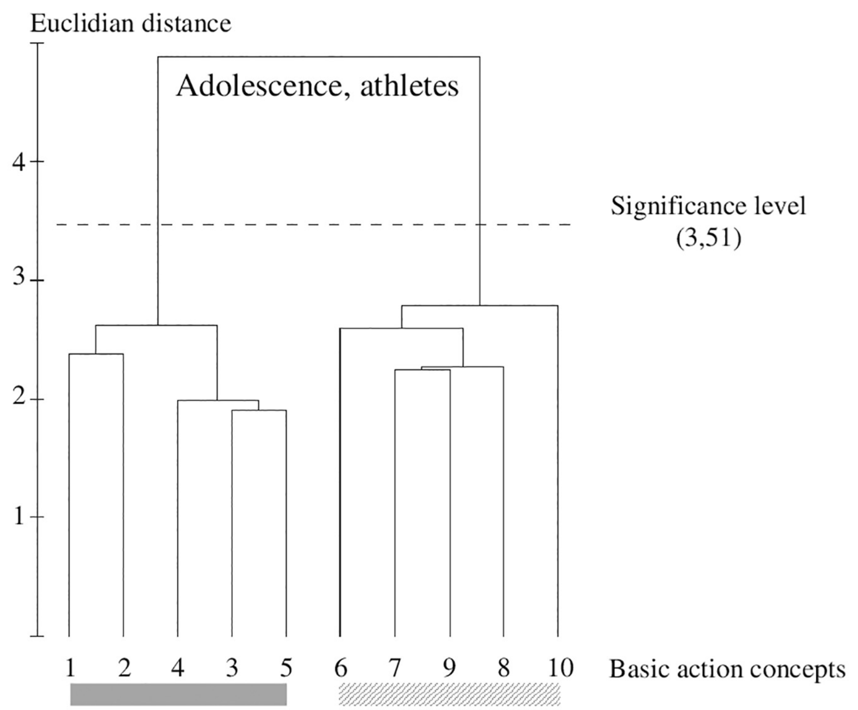
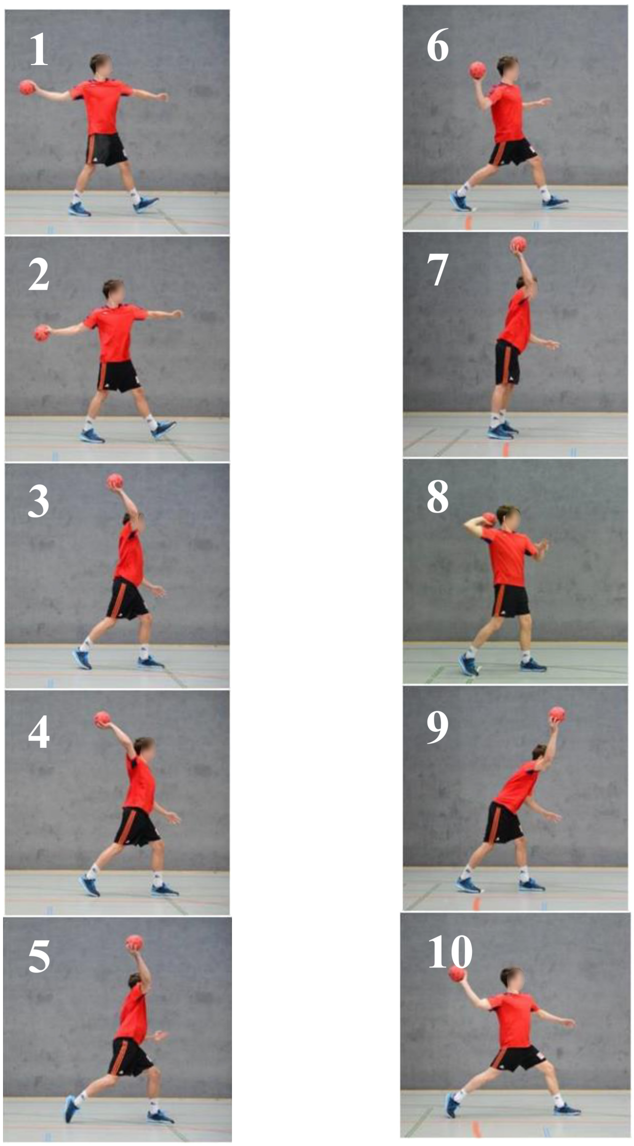


FIGURE 7 | Outcome of the hierarchical cluster analysis of athletes within adolescents (N = 20) displayed as a dendrogram. The dashed line clarifies the critical value of d_{crit} = 3.51, which corresponds to a significance level of 5%. The BACs are marked with numbers among the dendrogram and highlighted with the gray solid bar (technically correct BAC) and diagonally striped bar (faulty BAC).

TABLE 1 | The images used represent the BACs of the overhead throwing movement.

Technically correct movement	Technically faulty movement



The images were used in the SAD-M task. Images 1–5 present technically correct movements. Images 6–10 present typical errors in the overhead throwing movement. The picture number marks the BAC in the dendrogram. Concepts: 1–2 backswing; 3–5 throwing motion; 6 humerus oblique under shoulder; 7 no stepping; 8 backswing; 9 trunk forward-flexion; and 10 big step.

16 years remained on one level of development in the mental representation of the overhead throwing movement, which contradicts studies of De Waelle et al. (2021), Caeyenberghs et al. (2009), and Souto et al. (2020) who found age-related changes in the cognitive development.

Athletes up to the age of 12 years also demonstrated less structured mental representations. Clearly recognized is the development between childhood and pubescence of athletes. From the age of 13 years, athletes successfully separated technically correct and technically faulty overhead throwing movements. These representation structures were comparable with the ideal reference-cluster solution.

These results suggest an influence of cognitive improvement to movement development, which is consistent with the benefits in quantitative and qualitative movement characteristics. As hypothesized in this study, a growing expertise in throwing performance is accompanied by a development of the mental representation (Frank et al., 2016). With an increasing training level, children and adolescents showed a well-structured mental representation, that is, separating technically correct and technically faulty clusters. This outcome is in accordance with studies of Stoeckel et al. (2012) and Schack and Mechsner (2006). These results suggest that an improvement of the mental representation of the overhead throwing movement is accompanied by improvements in quantitative and qualitative characteristics (Gromeier et al., 2017, 2019). Hence, good performances in the quality and accuracy of movements are associated with a well-structured mental representation, that is, a clear separation in a technically correct and a technically faulty cluster. This confirms (Schmitz and Assaiante, 2002) in the way that a longer practice time develops an internal representation.

In contrast, the development of cognitive competences in overhead throwing movements is not linked to advancing age. It has been shown that between various levels of motor development (i.e., childhood, pubescence, and adolescents), no improvement could be recognized, and the novices stagnated on a low level of mental representation. Therefore, with increasing age, novices did not improve their mental representation as well as the quantitative and qualitative throwing performances (Gromeier et al., 2019). In sum, without an increased training, neither the throwing performance nor the associated mental representation is likely to improve further by itself or automatically. On the one hand, these findings contradict previous studies that found age-related differences in the development of the overhead throwing movement (Roberton and Langendorfer, 1980; Halverson et al., 1982; Winter, 1987; Roberton and Konczak, 2001; Lorson et al., 2013). In summary, these differences were found in throwing velocity, throwing accuracy, and movement quality characteristics.

TABLE 2 | Results (λ-values) of group analysis for cluster sets of each group.

Group	NC	NP	NA	HC	HP	HA	RG
NC		1	1	1	0.59	0.59	0.59
NP	1		1	1	0.59	0.59	0.59
NA	1	1		1	0.59	0.59	0.59
HC	1	1	1		0.59	0.59	0.59
HP	0.59	0.59	0.59	0.59		1	1
HA	0.59	0.59	0.59	0.59	1		1
RG	0.59	0.59	0.59	0.59	1	1	

Outcome of invariance analysis between the mental structures of each group. NC, novices group within childhood; NP, novices group within pubescence; NA, novices group within adolescents; HC, handball group within childhood; HP, handball group within pubescence; HA, handball group within adolescents; RG, reference group, λ_{crit} = 0.68.

On the other hand, these findings underline recent research on the development of mental representation structure, which has elicited functional changes in novices' representations as a result of physical and mental practice (Frank et al., 2014; Schack and Frank, 2021).

For physical education teachers and university sport lecturers, the results of this study imply that the development of complex motor skills, such as throwing movements, is not completed at the end of adolescents. Without specific interventions (e.g., technique practice), children and adolescents cannot evolve their cognitive and motor competences in throwing (Gromeier et al., 2019).

A reason can be found in the complexity of the overhead throwing movement. In learning processes of complex motor skills, children, youth, and adults are repeatedly confronted with excessive demands because of coordinative requirements (Hamilton and Tate, 2002). The optimal performance of overhead throwing movements requires precise mechanics that involve optimal execution of proximal-to-distal sequences to develop, transfer, and regulate the forces that are needed to withstand the inherent demands of the task (Kibler et al., 2013). To produce optimal speed and/or high accuracy at the distal end of the throwing arm, involved body segments have to be ordered in a specific way. The quality of overhead throwing movements highly depends of the object of throwing. In general, during the learning process of overhead throwing movements, educators must be ensured that the throwing object can be grasped with fingers and held securely with one hand. Regarding the physical education and university education, exercises should be applied purposefully, including individual instructions. To support the children in their motor development, the learning process should be supplemented by cognitive training to develop the mental representation of overhead throwing movements. To develop mental representation of a complex motor skill like the overhead throwing movement, there is evidence that physical education and training intervention should focus on random training (Fazeli et al., 2017). By comparing block and random practice, random training is more effective and could be beneficial in the transfer of learning to novel tasks (Jamieson and Rogers, 2000). The results suggested by Kim et al. (2017) supports the idea that being able to observe a new skill (e.g., throwing a ball) increases a person's ability to implement that motor skill. Cognitive-perceptual and performance changes were improved over time through to action observation training (Kim et al., 2017).

These outcomes can only be interpreted within the limits of a cross-sectional study, which allows only restricted statements on the development. Due to the young participants, it was necessary to simplify and adapt the SDA-M (i.e., a group of faulty BACs, and a group of correct BACs), and the generalizability of these findings is subject to certain limitations. Further studies should examine differences and similarities in the mental representation of the overhead throwing movement of different age-bands and expertise, comparing with qualitative, quantitative, and biomechanical data. To examine difficulties in movement pattern among novices, further studies should evaluate the qualitative development across time of single movement characteristics and effects of specific cognitive training interventions on movement pattern. Concerning athletes, future studies should investigate if the similarities and differences in the athletes' cognitive structures are also reflected in their motor performance. For both novices and experienced athletes, this can obtain further information on how to improve specific motions as well as on how to support an overall motor learning.

DATA AVAILABILITY STATEMENT

The raw data presented in this study are available upon reasonable request from the corresponding author (MG).

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee (”Ethik-Kommission”) at Bielefeld University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

MG: conception or design of the work, data collection, data analysis and interpretation, critical revision of the manuscript, and drafting the manuscript. TS: critical revision of the manuscript and final approval of the version to be published. DK: conception or design of the work, data analysis and interpretation, and critical revision of the manuscript. All authors contributed to the article and approved the submitted version.

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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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BRIEF RESEARCH REPORT
published: 27 May 2022
doi: 10.3389/fpsyg.2022.906336

Executive Functions and Mood States in Athletes Performing Exercise Under Hypoxia

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OPEN ACCESS

Edited by:
Maurizio Bertollo, G. d'Annunzio University of Chieti–Pescara, Italy

Reviewed by:
Francisco Miguel Leo, University of Extremadura, Spain
Maicon Rodrigues Albuquerque, Federal University of Minas Gerais, Brazil

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

Received: *28 March 2022*
Accepted: *09 May 2022*
Published: *27 May 2022*

Citation:
Guicciardi M, Pazzona R, Manca A, Monni A, Scalas LF, Perra F, Leban B, Roberto S, Mulliri G, Ghiani G, Doneddu A and Crisafulli A (2022) Executive Functions and Mood States in Athletes Performing Exercise Under Hypoxia. Front. Psychol. 13:906336. doi: 10.3389/fpsyg.2022.906336

Hypoxia can impair cognitive performance, whereas exercise can enhance it. The effects of hypoxia on cognitive performance during exercise appear to be moderated by exercise duration and intensity and by severity and duration of hypoxia and cognitive task. In normal individuals, exercise under hypoxia can evoke adverse post-exercise mood states, such as tension and fatigue. However, little is known about the effects of hypoxia during exercise in trained athletes. The purpose of this study was to investigate how hypoxia affected executive functions and mood states, assessed, respectively, during and post-exercise and to explore the role of motivation moderators, such as inhibition and activation systems (BIS-BAS). Two different sessions of exercise in normoxia and hypoxia (FiO2 13%), each lasting 18 min, were randomly assigned in a counterbalanced order and administered to seventeen male athletes. During exercise bouts, participants performed a mental task (BST) aimed to produce cognitive interference and suppression. Reaction times and accuracy of responses were recorded. After 5 min, all participants completed two questionnaires assessing mood states (ITAMS) and incidence of symptoms potentially related to hypoxia (AMS-C). The results show that hypoxia impairs cognitive performance in terms of slower reaction times, but a high BAS attenuates this effect. Participants with high BAS show an equivalent cognitive performance under hypoxia and normoxia conditions. No effects were found on mood states. Further research is required to investigate the role of BAS, cognitive abilities, and mood states in prolonged hypoxic conditions.

Keywords: executive functions, mood states, exercise, cerebral oxygenation, athletes, inhibition and activation systems

INTRODUCTION

Executive functions refer to the cognitive abilities involved in the initiation, organization and regulation of behaviors. Executive functions play a vital role in everyday life (McMorris et al., 2011) and are involved in goal-directed behavior, such as exercise (Colcombe and Kramer, 2003; Guiney and Machado, 2013). Scientific evidence suggests that, after a session of exercise requiring acute physical effort, athletes tend to score higher on cognitive tests than when they have not exercised

(Etnier and Chang, 2009) and the release of catecholamines was called into question to explain how a single bout of exercise affects cognitive performance (McMorris, 2016).

Although exercises performed at moderate intensity can enhance cognitive functions and prevent neurocognitive disorders (Brisswalter et al., 2002; Lambourne and Tomporowski, 2010), the improvement of the executive functions seems weaker when compared with other kinds of training (Diamond and Ling, 2019) and the interplay between physical and cognitive fatigue must be further investigated (McMorris, 2020; O'Keeffe et al., 2021). Moreover, if exercise takes place at altitude, cognitive performance can be negatively affected (Kramer et al., 1993; Virués-Ortega et al., 2004). Increasing altitude and the consequent severity of hypoxia may attenuate oxygen delivery to the brain tissue and that may result in impairment of brain functions and cognitive abilities (de Aquino Lemos et al., 2012; Diamond, 2013; McMorris et al., 2017), such as executive function, attention, episodic memory, and information processing (Roach et al., 2014; Turner et al., 2015).

Hypoxia is believed to impair cognitive performance (Ando et al., 2020) and it is both the consequence and the cause of many acute and chronic diseases, such as hypertension. As hypoxia levels and exposure time increase, reaction time, and error rate also increase in cognitive tasks (Li et al., 2000; Kourtidou-Papadeli et al., 2008). However, accumulating new evidence suggests that moderate hypoxia may have no adverse effects on cognitive function (Davranche et al., 2016; Morrison et al., 2019; Sun et al., 2019). Some scholars even found in sedentary young women that both exercise and short-term severe hypoxia could have beneficial effects on cognitive function (Lei et al., 2019).

The detrimental or beneficial effects of hypoxia on cognitive performance during exercise are primarily dependent on the interaction of moderators, such as exercise duration and intensity, severity, and duration of exposure to hypoxia and cognitive task type (Ando et al., 2020). In hypoxic conditions, such as high altitude, the acute mountain sickness (AMS) varies according to the duration of the exercise: as the exposure time increases, the discomfort experienced increases (DiPasquale et al., 2015). Several studies have shown that exposure to altitude can lead to increased depressive behavior, anger, fatigue, and irritability (de Aquino Lemos et al., 2012). Moreover, different psychological variables were assessed post-exercise executed in normobaric hypoxia, such as affective responses and mood states (Seo et al., 2015), but the results are still controversial. Keramidas et al. (2016) found that exercise in hypoxia leads to increased post-exercise tension and confusion, while many scholars reported an improvement in mood states (Seo et al., 2015) and positive affective responses (Pasco et al., 2011). Thus, some moderator variables, such as motivational ones, could account for these individual differences (McMorris, 2020). Specifically, a recent review evidenced how it is important to understand the interaction between the motivation and performance in athletes through the study of the EEG prefrontal asymmetry, a biomarker of approach and avoidance motivations (Haehl et al., 2022) and largely related in literature with the BIS and BAS motivational traits (for a review, Vecchio and De Pascalis, 2020). BIS and BAS are two neuropsychological and motivational systems that regulate behavior and emotions: the Behavioral Inhibition System (BIS) regulates avoidance motivation, and the Behavioral Activation System (BAS) regulates approach motivation. The BIS is related to negative emotions (e.g., anxiety, fear, sadness) that might be activated by negative environmental cues of possible punishing, novel, or non-rewarding situations (Gray, 1987, 1990; Carver and White, 1994). The activation of the BIS determines inhibition of behavior that may somehow lead to negative or potential painful outcomes. The BAS is at the basis of approach motivated behaviors toward appetitive goals and is related to positive emotions (e.g., elation, happiness, hope) anticipated by rewarding-positive cues in the environment (Gray, 1990; Carver and White, 1994).

In our previous studies (Mulliri et al., 2020; Magnani et al., 2021) a different duration and intensity of exercise, severity and duration of exposure to hypoxia were considered in samples of young healthy males. Using an interference cognitive task (Guicciardi et al., 2019, 2020), the present study aimed to ascertain in a group of highly trained male athletes how acute hypoxia during exercise affects cognitive functions and post-exercise mood states and if these relationships were moderated by the BIS-BAS systems. *Inter alia*, we hypothesized that: (a) compared to normoxic conditions, exercise performed under hypoxia impairs cognitive performances; (b) under hypoxia conditions, participants' reaction times increase as the number of trials increases; (c) hypoxia condition is associated with more negative mood states; (d) inhibition and activation systems (BIS-BAS) can moderate the relationship between exercise performed under hypoxia-normoxia conditions and cognitive performances.

MATERIALS AND METHODS

Sample

A group of 17 male athletes was involved (age m = 30.24; sd = 6.63) based on the following criteria: being involved in regular physical endurance training for at least 3 years and for at least 8 h/week; age between 18 and 45 years; absence of any chronic cardiopulmonary, metabolic, or neurological diseases. 14 athletes have completed the protocol while 3 dropped out prematurely. All athletes were screened to exclude some cognitive deficits and to assess initial signs of discomfort, such as acute mountain sickness, after experiencing hypoxia. This study was performed according to the recommendations of the Code of Ethics for Research in Psychology, Italian Association of Psychology and in accordance with the Declaration of Helsinki. The protocol was approved by the ethics committee of the University of Cagliari (UniCA prot. 0073832).

Measures

The *Acute Mountain Sickness Cerebral* (AMS-C), developed by Beidleman et al. (2007) is a self-reported 11-items inventory, used to evaluate a weighted AMS cerebral factor score. This condition can be present if an individual's AMS-C score is > 0.7. In the present study, Cronbach's alpha is AMS-C = 0.95.

The *Behavioral Inhibitions System and The Behavioral Activation System* (BIS-BAS) were developed by Carver and White (1994) to evaluate the behavioral inhibition and activation systems described by Gray (1987, 1990). It is composed of 20 items with a 5-point Likert scale response format (1 = It does not describe me at all, 5 = It completely describes me). The BIS explores anxious anticipation of negative events (7 items). The BAS investigates the reward sensitivity with three factors: BAS Drive that assesses proactive behaviors (4 items, BASd); BAS Reward Responsiveness explores the tendency to be excited by reward opportunities (5 items, BASrr); and BAS Fun Seeking that investigates the tendency to experiment new sensations (4 items, BASfs). The Italian version showed an acceptable internal reliability (Cronbach's alphas are BASd = 0.68, BASfs = 0.75, BASrr = 0.74, BIS = 0.72) (Leone et al., 2002). In the present study Cronbach's alphas are BASd = 0.62, BASfs = 0.60, BASrr = 0.69, BIS = 0.82.

The *Bivalent Shape Task* (BST) developed by Esposito et al. (2013) is a simple non-verbal measure of cognitive interference and suppression in which participants must indicate whether a shape in the center of the screen is a square or a circle. Two response targets are provided for each stimulus, one in the shape of a circle and one in the shape of a square. The participant, equipped with a mouse, is asked to click the response target corresponding to the center of the screen stimulus and target color. The stimulus shape is presented in red, blue, or an unfilled black outline; response targets can be presented in red or blue. Three trial types exist: neutral (black or white stimulus); congruent (the stimulus color matches the response target color); incongruent (the stimulus color mismatches the response target color). The response times were recorded in ms.

The *Italian Mood Scale* (ITAMS) was developed by Quartiroli et al. (2017) to evaluate six mood states relevant in sport and exercise: anger, confusion, depression, fatigue, tension, and vigor. The ITAMS is composed of 24 items expressing mood descriptors with a 5-point Likert scale response format (0 = "not at all", 4 = "extremely"). Each mood state is assessed through six items. In the present study Cronbach's alphas are anger = 0.74; confusion = 0.83; depression = 0.63; fatigue = 0.91; tension = 0.67; vigor = 0.87.

The *Positive and Negative Affect Schedule* (PANAS) was developed by Watson et al. (1988) is used to investigate positive (PA) and negative (NA) affect. The PANAS consists of a list of 20 adjectives of which 10 refer to PA (e.g., enthusiastic, interested, and determined) and 10 to NA (e.g., afraid, upset, distressed). All items are rated on a 5-point Likert scale response format (1 = "very little or not at all", 5 = "very much"). We used the Italian version (Terracciano et al., 2003). In the present study Cronbach's alphas are PANp = 0.76, PANn = 0.86.

The *Rating of Perceived Effort Scale* (RPE) developed by Borg (1982) is used to quantify an individual's perception of the physical effort of an activity. The scale consists of intervals from 6 (no exertion at all) to 20 (maximal exertion).

The *Trail Making Test* (TMT) developed by Reitan (1955) is a neuropsychological test that evaluates visual search scanning, speed of processing, mental flexibility, and executive functions. The TMT consists of two parts: A and B. TMT-A requires drawing lines sequentially connecting 25 encircled numbers distributed on a paper sheet. During the TMT-B the participant must draw lines alternating numbers and letters. The score on each part represents the amount of time required to complete the task and any errors made. In our study, we used the Italian version (Giovagnoli et al., 1996).

Procedure

All participants were assessed on two occasions: baseline visit and experimental phase. During the baseline visit, every participant underwent a medical examination with anamnesis, anthropometric measures (height, weight, and body composition) and psychological assessment. All participants performed an exhaustion cardiopulmonary exercise test on a cycle ergometer (Monark 828E, Vansbro, Sweden), to fix the threshold at which to carry out the exercise in the experimental phase. Specifically, the workload at the gas exchange threshold was calculated (Mulliri et al., 2020; Magnani et al., 2021). To exclude previous cognitive deficits and to assess the perceived exertion or potential emotional discomfort produced by the incremental exercise, TMT, RPE and PANAS were, respectively, administered. Finally, BIS/BAS was administered.

The experimental phase started after 7 days from the baseline visit and included two sessions counterbalanced in reverse order: hypoxia and normoxia. Participants did the BST while pedaling in a sitting position on the cycle ergometer. The responses to the BST were provided through a mouse positioned on a table adjacent to the cycle ergometer (dual task). Finally, they cooled down and recovered while sitting on the cycle ergometer for another 6 min. This procedure was done to minimize possible psychological influences from exposure to hypoxia. Lastly, ITAMS and AMS-C were administered to assess, respectively, mood states post-exercise and to exclude that the inhalation of hypoxic gas could have jeopardized the wellbeing of the athletes.

Data Analysis

We used SPSS software Version 24.0 (SPSS Inc., Chicago, IL, United States) for all statistical analyses. Preliminary checks were done on TMT scores and PANAS scores, respectively, to exclude previous cognitive deficits or strong adverse mood states post-exercise due to incremental test. Then, we conducted repeated measures analysis on AMS-C scores to exclude that the experimental manipulation has produced initial signs of discomfort. After that, we conducted a repeated measure ANOVA with Greenhouse-Geisser correction to assess if the reaction times differ between the hypoxia and normoxia across four conditions. We explored the trend of time reactions over incremental trials through linear regression analyses, and we performed paired sample t-tests of time reactions for low vs. high BAS groups across hypoxia-normoxia conditions. Before running the analyses, we preliminarily tested the assumptions. For ANOVA and paired t-tests the data were checked for outliers and normal distribution through the Shapiro-Wilk test. We excluded two outliers (3rd quartile + 3*interquartile range 1st quartile–3*interquartile range), trial 1 for BASfs hypoxia neutral condition and trial 23 for BASrr normoxia congruent condition. Our data were normally distributed except for the BIS hypoxia mixed condition (Shapiro Wilk test $p < 0.000$), which was excluded from the final analyses. For linear regression analyses, we tested the assumptions of normality, linearity, homoscedasticity, and the absence of multicollinearity. All assumptions were met. To calculate the *post hoc* power analysis we employed the G*Power 3.1.9.7 (Faul et al., 2009).

RESULTS

Descriptive Statistics of Perceived Effort, Executive Functions, and Accuracy

Preliminarily, we calculated the descriptive statistics to evaluate the individual's perception of the physical effort on activity (RPE), the executive function measured with the TMT, the PANAS to assess the onset of significant negative affect and the accuracy level reached by all participants in performing the BST task. This was evaluated to exclude that an excessive effort, a scarce cognitive function, a momentary negative affect, or a reduced accuracy might invalidate the other results. The individual's effort perception indicates a medium level of effort (m = 16.4; sd = 1.4); participants exhibited normal cognitive abilities (TMT_A m = 29.8; sd = 5.4; TMT_B m = 90.1; sd = 27.6; TMT_BmA m = 72.6; sd = 36.4; cut-off TMT_A = 94; TMT_B = 283; TMT_BmA = 187); the average negative affect (m = 14.18, sd = 3.84) is consistent with the Italian normative data (m = 15.0, sd = 5.5) of a non-clinical sample (Terracciano et al., 2003); and average accuracy is over 99% for the majority of BST condition (min = 97.6, max = 100).

We further explored whether a momentary discomfort occurred, we calculated a repeated measure ANOVA of AMS-C measures and we did not find any significant difference on hypoxia versus normoxia condition [$F(1, 13) = 3.4$, $p > 0.05$].

Comparison of the Hypoxia and Normoxia Conditions

The repeated measures ANOVA, with Greenhouse-Geisser correction, showed that the reaction times for the BST Pure Incongruent condition differ between the hypoxia vs. normoxia condition [$F_{(1,\ 14)} = 6.797$, $p < 0.05$; *post hoc* power = 0.637]. Specifically, a Bonferroni correction *post hoc* analysis evidenced that participants in the BST Pure Incongruent conditions, under hypoxia condition, employed on average 117.3 ms more than normoxia condition (Hypoxia m = 942.5; sd = 196.7; Normoxia m = 825.2; sd = 146.9). This difference is statistically significant (p = 0.027). Comparison between hypoxia and normoxia across the other BST conditions did not reach significant differences.

Since the number of subjects who completed the study was small, we opted to consider trials (not subjects) as the number of observations. To obtain the observations we averaged the reaction times of each trial across all participants under hypoxia and normoxia conditions (for example, RT trial 1 for hypoxia condition-first observation-was obtained by averaging the reaction time at trial 1 of 1–14 participants under hypoxia condition). We obtained 10 variables: RT of Hypoxia, Normoxia conditions and RT of Neutral, Congruent, Incongruent, and Mixed conditions under hypoxia and normoxia (average of N = 25.5 trials' reaction times for Neutral, Congruent and Incongruent conditions under hypoxia and normoxia and an average of N = 74.5 for Mixed condition under hypoxia and normoxia). This method has the advantage of increasing the number of observations and exploring whether reaction times progressively change from the first to the last trial. Conversely, employing subjects as observations we necessarily had to have a single reaction time measure (averaging all reaction times from the first to the last trials), losing the variability across the trials.

Preliminarily, we compared the hypoxia and normoxia conditions in a paired sample t-test. We observed that hypoxia and normoxia differ significantly [$t_{(73)} = 2.948$, $p = 0.004$; *post hoc* power = 0.830], the hypoxia condition is characterized by an enhanced reaction time than normoxia condition (Hypoxia m = 829.4; sd = 95.4; Normoxia m = 795.3; sd = 83.8).

Secondarily, we compared the four conditions under hypoxia and normoxia. We observed that in a paired sample t-test the BST Pure Incongruent condition was significantly different between hypoxia and normoxia [Pure Incongruent $t_{(22)} = 3.962$, $p = 0.001$; *post hoc* power = 0.965].

Specifically, participants in the BST Pure Incongruent conditions, under hypoxia condition, employed on average 94.5 ms more than in normoxia condition (Hypoxia m = 903.3; sd = 139.2; Normoxia m = 808.8; sd = 81.50). This difference is statistically significant (p = 0.001). Comparison between hypoxia and normoxia across the other BST conditions did not reach significant differences.

Subsequently, to explore whether reaction times progressively changed, we analyzed the trend of time reactions over incremental trials. We hypothesized that, under hypoxia conditions, participants' reaction times increase as the number of trials increases. After calculating the linear regression, we found the opposite result in both conditions, such that participants' reaction times reduce as the number of trials increases (see **Table 1**).

Therefore, although under both hypoxia and normoxia reaction times progressively reduce with the number of trials, we noticed that the hypoxia condition was characterized by slower time reactions at the beginning in comparison to the normoxia condition. That is, subjects under hypoxia condition are slower in responding to the first trials compared to normoxia condition.

Moreover, no significant differences were found through Repeated measure ANOVA comparing each subscale of the ITAMS between the hypoxia vs. normoxia conditions [ITAMS anger $F_{(1,\ 14)} = 2.37$, $p > 0.05$; ITAMS confusion $F_{(1,\ 14)} = 0.75$, $p > 0.05$; ITAMS depression $F_{(1,\ 14)} = 0.32$, $p > 0.05$; ITAMS fatigue $F_{(1,\ 14)} = 1.36$, $p > 0.05$; ITAMS tension $F_{(1,\ 14)} = 0.00$, $p > 0.05$; ITAMS vigor $F_{(1,\ 14)} = 1.19$, $p > 0.05$]. Therefore, the hypothesis that the hypoxia condition is associated with a more negative emotional status was not supported.

Moderation of Cognitive Performance Conditions by Motivational Systems Under Hypoxia and Normoxia

We observed that the Behavioral Activation Sensitivity (BAS) significantly influenced the BST performance under hypoxia-normoxia conditions. We compared the time reactions from the first to the last trial of the BST task under hypoxia and normoxia conditions. We were interested in exploring differences across high and low BIS-BAS traits, thus we divided participants in two groups for each BIS/BAS subscale. First, we calculated the descriptive statistics of the four BIS-BAS scales, for the high groups, we selected only participants who scored one standard deviation above the mean, for the low groups, we selected only participants who scored one standard deviation below the mean of each BIS-BAS scale (high and low BAS drive; high and low BAS reward responsiveness etc.) (Blood and Blood, 2007; **Table 2**). After obtaining these two groups for each BIS-BAS scale we averaged the reaction times of each trial across these participants under hypoxia and normoxia conditions following the method described in paragraph 3.2.

We then compared the two conditions in a paired sample *t*-test. For low BAS groups we observed the same pattern of results that emerged in the previous analyses, such that hypoxia and normoxia significantly differ. Interestingly, for the high BAS groups the difference between hypoxia and normoxia disappears (**Table 3**).

Specifically, high BAS participants exhibited an equivalent performance on the Pure Neutral and Congruent conditions under hypoxia and normoxia. In the Mixed condition, we detected a more substantial difference between low BAS groups, which exhibited a different performance in the hypoxia-normoxia conditions, and high BAS groups, which exhibited an equivalent performance (see **Figure 1**). The Incongruent condition was not affected by high or low BAS.

TABLE 1 | Linear regression between reaction times and trials number.

		B	*SD*	β	t	*p*
RThypoN	(Constant)	1023.1	59.2		17.3	0.000
	TRIAL	−12.7	4.1	−0.546	−3.1	0.006
RThypoC	(Constant)	859.5	35.7		24.1	0.000
	TRIAL	−6.8	2.3	−0.516	−2.9	0.007
RThypoI	(Constant)	1027.8	50.4		20.4	0.000
	TRIAL	−9.864	3.5	−0.512	−2.8	0.011
RThypoM	(Constant)	913.7	21.2		43.2	0.000
	TRIAL	−2	0.5	−0.436	−4.1	0.000
RTnorN	(Constant)	977	49.9		19.6	0.000
	TRIAL	−11.9	3.1	−0.607	−3.8	0.001
RTnorC	(Constant)	848	31.6		26.8	0.000
	TRIAL	−8.2	1.9	−0.644	−4.3	0.000
RTnorI	(Constant)	890.1	29.1		30.6	0.000
	TRIAL	−6.9	2.1	−0.590	−3.4	0.002
RTnorM	(Constant)	864.7	17.2		50.4	0.000
	TRIAL	−1.4	0.4	−0.385	−3.5	0.001

RT, reaction times; hypo, hypoxia condition; nor, normoxic condition; I, incongruent; N, neutral; C, congruent; M, mixed (incongruent, congruent, and neutral).

TABLE 2 | BIS-BAS descriptive statistics and number of participants included in the high or low BIS-BAS groups.

	Min	Max	Mean	*SD*	High group *N*	Low group *N*
BASd	2.25	4.25	3.43	0.47	5	6
BASfs	2.25	4.50	3.47	0.61	4	4
BASrr	3.00	5.00	4.38	0.47	5	6
BIS	2.14	5.00	3.31	0.76	4	6

DISCUSSION

The most frequent psychological disorders caused by acute physical exercise in a condition of hypoxia are related to the cognitive and emotional aspects. For this reason, monitoring psychological responses in similar situations can represent an indicator of the adverse effects that brain desaturation entails, acting as a predictor of performance.

Currently, the effects of physical exercise in acute hypoxic conditions on cognitive processes and mood states are inconsistent. This could be due to methodological and experimental differences (Jung et al., 2020). The goal of this study was to gain an understanding of the impact of physical exercise in acute hypoxic conditions on cognitive functions and mood states, introducing motivational systems as potential moderators.

The repeated measures ANOVA, with Greenhouse-Geisser correction, showed that participants in the BST Pure Incongruent conditions, under hypoxia condition, exhibited slower RT compared to normoxia condition (on average 117.3 ms more).

Employing trials as observation we confirmed the previous result in a *t*-test corroborating the difference between the hypoxia and normoxia, particularly under Incongruent and Mixed conditions.

Contrary to our second hypothesis, according to which hypoxia progressively worsens reaction times, we found that under both conditions reaction times progressively reduce with trial numbers. However, we noticed that, at the beginning, the hypoxia condition is characterized by slower reaction times in comparison to the normoxia condition. That is, subjects under hypoxia conditions are slower in responding to the first trials compared to normoxia conditions. This paradoxical result can be explained by different factors, such as a learning/habituation effect or by the contribution of cognitive fatigue (McMorris, 2020). As already noted, "individual may predict the sensory consequences during submaximal exercise as being more demanding than in a maximal performance task, where the perceptual demands are less" (McMorris, 2020, p.1706).

Our third hypothesis that the hypoxic condition is associated with more negative mood states was not confirmed. Unlike other studies, we found no effects on mood states. Previous studies have reported in hypoxic conditions an increase in anger, depression and fatigue (Lane et al., 2005), such as an increase in fatigue and a reduction of vigor (Legg et al., 2016) or an increase in tension and confusion when exercise was performed under hypoxic conditions

TABLE 3 | Paired sample *t*-test of time reactions BST for low vs. high BAS groups across hypoxia-normoxia conditions.

RT BST	**Low**						**High**					
Neutral	***HYPO mean (sd)***	***NOR mean (sd)***	***t***	***df***	***P***	***Power***	***HYPO mean (sd)***	***NOR mean (sd)***	***t***	***df***	***P***	***Power***
Basd	1014.12 (217.01)	880.31 (183.27)	3.60	20	0.002	0.928	810.84 (177.6)	766.3 (146.52)	1.60	23	0.124	0.334
Basfs	938.01 (144.37)	803.77 (97.65)	4.66	19	0.000	0.999	758.38 (105.86)	811.96 (205.88)	-1.22	22	0.235	0.050
Basrr	934.88 (191.76)	822.77 (135.19)	4.44	21	0.000	0.984	781.72 (137.46)	798.10 (174.51)	−0.41	22	0.684	0.068
Bis	889.43 (217.85)	846.66 (184.22)	1.22	23	0.234	0.249	859.18 (159.92)	841.82 (177.08)	0.39	22	0.698	0.066
Congruent	***HYPO mean (sd)***	***NOR mean (sd)***	***t***	***df***	***p***	***Power***	***HYPO mean (sd)***	***NOR mean (sd)***	***t***	***df***	***p***	***Power***
Basd	863.09 (94.85)	802.15 (91.71)	2.45	22	0.023	0.649	694.58 (115.51)	681.61 (87.88)	0.59	24	0.563	0.117
Basfs	815.04 (115.31)	753.45 (74.29)	2.19	23	0.039	0.562	708.19 (149.99)	750.88 (134.98)	−1.50	24	0.146	0.302
Basrr	831.11 (118.81)	741.43 (61.44)	3.27	23	0.003	0.897	681.68 (99.12)	685.10 (88.60)	−0.13	23	0.897	0.051
Bis	733.67 (124.49)	735.01 (85.49)	−0.06	24	0.953	0.050	770.66 (118.76)	777.01 (134.26)	−0.18	24	0.860	0.053
Incongruent	***HYPO mean (sd)***	***NOR mean (sd)***	***t***	***df***	***p***	***Power***	***HYPO mean (sd)***	***NOR mean (sd)***	***t***	***df***	***p***	***Power***
Basd	972.65 (161.04)	889.5 (106.46)	2.26	23	0.034	0.581	868.08 (199.68)	732.79 (97.71)	3.43	23	0.002	0.907
Basfs	926.32 (131.27)	838.34 (95.23)	2.72	23	0.012	0.741	854.26 (185.45)	777.75 (116.76)	2.11	23	0.046	0.523
Basrr	827.75 (120.31)	742.37 (62.64)	3.02	22	0.006	0.896	767.19 (129.39)	748.44 (204.07)	0.42	23	0.681	0.068
Bis	928.16 (249.11)	787.34 (86.72)	3.17	23	0.004	0.858	848.14 (127.29)	832.25 (252.87)	0.30	23	0.764	0.061
Mixed	***HYPO mean (sd)***	***NOR mean (sd)***	***t***	***df***	***p***	***Power***	***HYPO mean (sd)***	***NOR mean (sd)***	***t***	***df***	***p***	***Power***
Basd	940.23 (139.83)	848.41 (88.78)	4.89	64	0.000	0.998	766.66 (116.14)	758.78 (100.15)	0.48	63	0.633	0.075
Basfs	875.56 (136.95)	805.97 (86.64)	3.94	69	0.000	0.973	796.25 (134.75)	818.89 (150.44)	−1.05	73	0.297	0.179
Basrr	880.72 (141.57)	801.98 (90.18)	4.21	69	0.000	0.986	741.27 (130.98)	769.62 (114.56)	−1.27	73	0.207	0.241
Bis	824.83 (133.11)	806.89 (102.95)	0.96	73	0.343	0.156	821.19 (134.97)	813.29 (126.81)	0.34	70	0.737	0.062

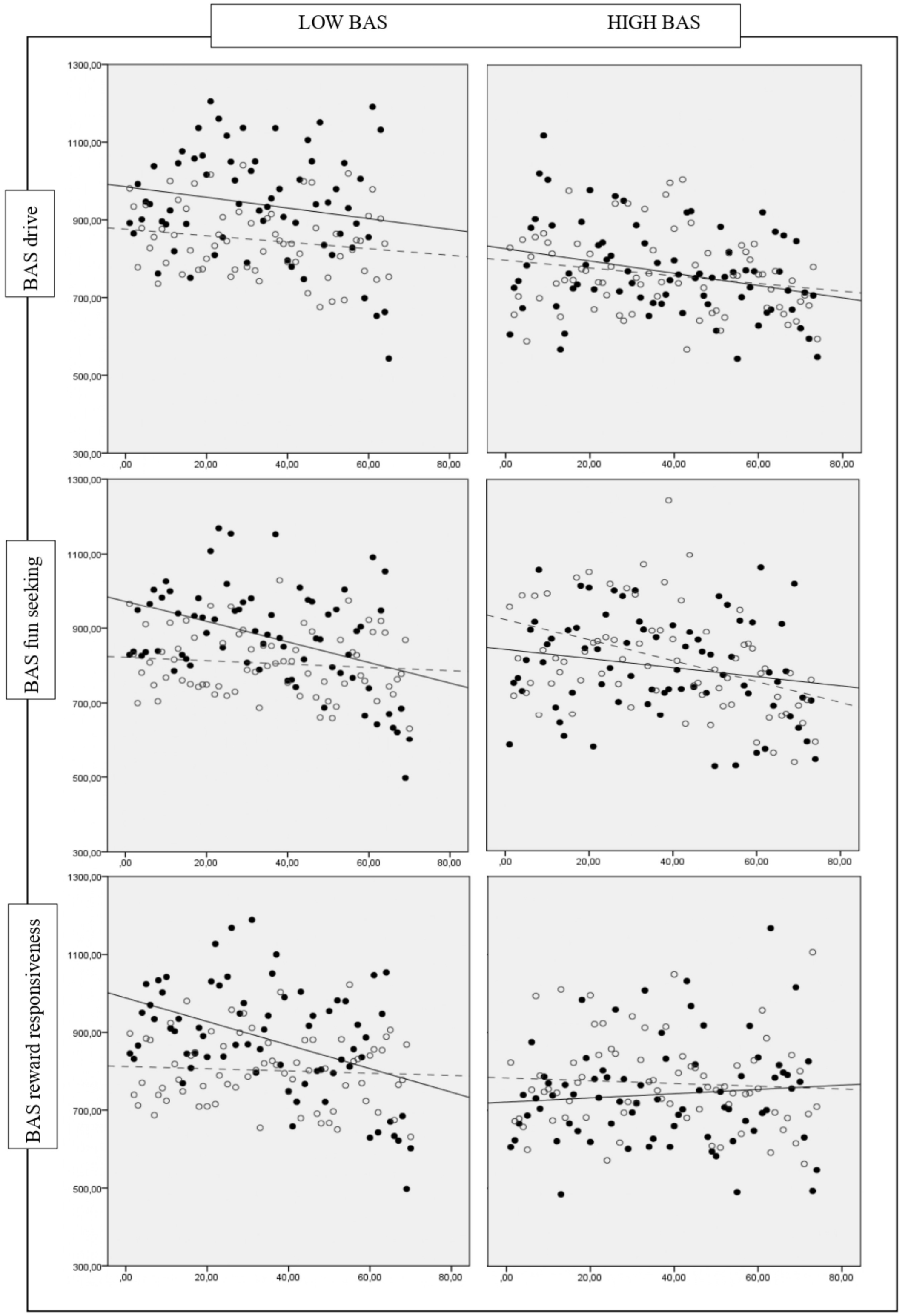

FIGURE 1 | Comparison between the average RT of individuals that perform Hypoxia (black dots and solid line) and Normoxia condition (gray dots and dashed line) across low vs. high BAS groups (drive, fun seeking or reward responsiveness) in the BST Mixed condition. Black dots and solid line, average RT per trials of individuals that perform hypoxia condition; Solid line, trend of average RT on hypoxia condition; Gray dots and dashed line, average RT per trials of individuals that perform normoxia condition; Dashed line, trend of average RT on normoxia condition x, trials numbers; y, time reactions in milliseconds.

(Keramidas et al., 2016). However, such studies differ for duration and severity of hypoxic conditions and exercise, for environmental conditions where the observations were executed (altitude vs. laboratory) and for the levels of physical skills of participants. For example, Keramidas and colleagues (2016) underwent an exhaustion test in hypoxic conditions, while in our study the athletes inhaled hypoxic gas in a condition parametrized to 70% of the maximum threshold. Seo et al. (2015) hypothesized that the mood state in hypoxia would be impaired following 60 min of hypoxic exposure, but would be improved during the two cycle ergometer exercise intensities (40 and 60% VO2max) and recovery. Based on our previous studies (Mulliri et al., 2020; Magnani et al., 2021) we decided to administer the hypoxic condition for 18 min. Thus, we cannot exclude that increasing the time of hypoxic exposure or reducing the exercise intensities could affect mood states post-exercise such as vigor, fatigue, tension, and confusion.

Our final hypothesis was related to exploring the effect of motivational systems in the relationship between exercise, hypoxia, and cognitive performance. While BIS appeared not involved in this relationship, we observed a relevant effect of BAS. For the low BAS groups, we observed the same pattern of results that emerged in the first analyses, such that hypoxia and normoxia significantly differ. However, for the high BAS groups, the difference between hypoxia and normoxia disappears. High BAS participants exhibited an equivalent performance in the Neutral, Congruent and Mixed conditions under both hypoxia and normoxia. The Mixed condition evidenced the more substantial difference between the low BAS and high BAS groups. The results of individuals with high BAS can be interpreted according to Gray's conception of individual differences (1990). According to the author, people may have a different sensitivity to BIS and BAS systems. In particular, those with BAS sensitivity tend more frequently to approach potentially rewarding stimuli and their ability to inhibit approach behavior near goals decreases, showing more impulsive behaviors. Therefore, since the BAS is considered an accelerator of approach behavior (Carver et al., 2015), it seems plausible that people with high BAS will show slower reaction times, regardless of the experimental condition, since this is a manifestation of their typical functioning.

The application and generalization of the present study need to be interpreted with caution since only highly trained male athletes were recruited for this investigation. Other limitations are represented by the duration of the exposure to the condition of hypoxia, the low reliability of some subscales, and the small size of the sample that should be increased. In further studies, the role of cognitive fatigue, interoceptive response, physiological correlates, and genetic variations should be deepened to better explain as the inhibition and activation systems moderate the interplay between hypoxia, exercise, cognitive performance, and mood states.

The results of the present investigation could be relevant not only for the application of optimal training protocols or to enhance the performance and safety of recreational and work activities during hypoxia but also from a clinical perspective as it provides insights on the interplay of cognitive, emotional and motivational variables that affect people with chronic diseases during exercise, rendering them hypoxic, such as COPD patients. Future research should investigate the role of BAS, cognitive abilities and mood states in prolonged hypoxic conditions; considering that a longer exposure time leads to an increasing worsening, this methodological change would allow for a more in-depth evaluation.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee UniCa–Prot. n. 0073832 March, 30 2021–(Classif. II/9). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AC and MG made the original study design and discussed with the other authors. FP performed the literature analysis. RP and AMa collected the psychological data. SR, GM, GG, AD, and BL collected the biomedical and postural data. AMo performed data analysis. LS conducted the formal analysis. MG, RP, and AMa wrote, reviewed, and edited the manuscript. All authors contributed to the article and approved the submitted version.

FUNDING

This study was supported by the Fondazione di Sardegna CUP: F74I19000990007 year 2018, title of the project: Effects of acute hypoxia on cardiovascular regulation and cognitive functions in athletes.

ACKNOWLEDGMENTS

This is a short text to acknowledge the contributions of specific colleagues, institutions, or agencies that aided the efforts of the authors.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.906336/full#supplementary-material

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ORIGINAL RESEARCH
published: 31 May 2022
doi: 10.3389/fpsyg.2022.906300

Sport Participation and Psychosocial Factors Which Influence Athletic Identity in Youth Athletes With Anterior Cruciate Ligament Injury

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OPEN ACCESS

Edited by:
Sergio Machado, Federal University of Santa Maria, Brazil

Reviewed by:
Julie Burland, University of Connecticut, United States
Aurelio Olmedilla, University of Murcia, Spain

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

Received: *28 March 2022*
Accepted: *12 May 2022*
Published: *31 May 2022*

Citation:
McGinley J, Stapleton E, Worrall H, Ellis HB, Wilson PL and Ulman S (2022) Sport Participation and Psychosocial Factors Which Influence Athletic Identity in Youth Athletes With Anterior Cruciate Ligament Injury. Front. Psychol. 13:906300. doi: 10.3389/fpsyg.2022.906300

Athletic identity, or the degree with which individuals identify with the athlete role, is an important rehabilitation factor for sports care providers to consider; however, it lacks extensive study in youth. The purpose of this study was to identify demographic, sport participation, and psychosocial measures which correlate with youth athletic identity after anterior cruciate ligament injury. Participants completed standardized sports medicine intake and patient-reported outcome measures, including the Athletic Identity Measurement Scale (AIMS). A total of 226 participants were included, and two groups were created based on high or low total AIMS score. Results indicated that sex ($p = 0.002$), years active in sport ($p = 0.049$), activity level ($p = 0.038$), and ACSI-Coachability ($p = 0.027$) differed by AIMS score. While youth athletes appear resilient, these results emphasize that they identify strongly with the athlete role and may suffer psychosocial consequences after injury. Future work should evaluate similar factors over course of recovery in a larger, diversified population.

Keywords: athletic identity measurement scale, adolescent, return to sport, psychology, rehabilitation, athletic identity

INTRODUCTION

Sports are an integral part of life for many children. Youth athletes' involvement in sport varies – for some it is the sole basis of friendships and recreation, for others it is merely a hobby (McKay et al., 2019). Sports may confer strong benefits to the participant in the avenues of physical health, teamwork development, and mental improvement (Panza et al., 2020). However, participation in sport for elite athletes may result in time commitments that conflict with other aspects of life, such as quality time for peer connections and academics (Eime et al., 2013). Furthermore, injuries may occur in both elite and recreational athletes which result in loss of the benefits and identity of sports participation and in dedicating a significant amount of time to injury rehabilitation (Christino et al., 2015). Therefore, a child's integration and involvement with sport may be a primary determinant of overall well-being, and identification of this association may assist health care providers when planning treatment strategies and/or anticipating response to treatment. This strong relationship with sport may be characterized as athletic identity, first defined by Brewer et al. (1993) as the degree with which individuals identify with the athlete role.

The association of athletic identity and specific demographic characteristics is poorly described in the literature. Some studies suggest that sex is significantly correlated with athletic identity in youth (Anderson et al., 2009) and young adults (Babić et al., 2015; Şekeroğlu, 2017). Yet, others claim there is no correlation with athletic identity in youth (Padaki et al., 2018; Piatt et al., 2018). In young adults, Lamont-Mills and Christensen (2006) saw no correlations with athletic identity, while Proios et al. (2012) observed differences only in the subcategory of how exclusive athletes were to their athletic identity over other identities. Association of athletic identity and race or ethnicity in the youth population is also poorly defined, though Anderson et al. and others suggest that Hispanic and minority youths perceive themselves as having lower athletic identity (Anderson et al., 2009, 2011; Edison et al., 2021). Youth athletes appear to conflate athletic identity and personality as they mature (Von Rosen et al., 2018; Newton et al., 2020; Edison et al., 2021), though athletic identity may begin to decrease with age at the undergraduate level (Renton et al., 2021). The convergence of athletic identity and personality in youth may prove problematic if their athletic identity is interrupted. Upon transition out of sport, being cut from a team, or experiencing an injury, athletes may feel a major aspect of their personality is unfulfilled, especially as single-sport specialization becomes more common with increasing age (Jayanthi et al., 2013).

Similarly, athletic identity and sport participation are not clearly related; however, the literature suggests increased training hours may significantly increase athletic identity (Piatt et al., 2018; Quinaud et al., 2020). Conversely, there has been conflicting data regarding athletic identity as a driving determinant of activity level (Reifsteck et al., 2013; Ohji et al., 2021). Ultimately, the relationship of athletic identity and patient-reported sport participation measures is unclear (Ardern et al., 2014).

Coping and fear of re-injury are likely associated with athletic identity, though the available literature is limited. Emotional trauma and depressive symptoms have been shown to increase with greater athletic identity in youth samples after injury (Manuel et al., 2002; Padaki et al., 2018). Additionally, McKay et al. (2013) noticed differences in injury patterns after youth ice hockey players underwent anterior cruciate ligament (ACL) injury.

There are unclear associations between athletic identity and demographics or psychological readiness within the spectrum of recreational to elite youth athletes due to the overall sparse literature. As such, sports care providers may have inadequate insight on psychological responses to injury and treatments within the adolescent population with differing levels of athletic identity. Therefore, the purpose of this study was to identify demographic, sport participation, and psychosocial measures associated with athletic identity in a youth athlete population after anterior cruciate ligament injury.

MATERIALS AND METHODS

This study was approved by the local Institutional Review Board (IRB; #STU-2019-0701). Informed consent was not required and was waived by the IRB as this study only consisted of a retrospective review of previously collected data.

Participants

A consecutive review of participants between the ages of 10.5 – 24.9 years (mean 15.9 years) who presented to a pediatric sports medicine practice and completed the standardized sports medicine intake and patient-reported outcome (PRO) measures between October 2019 and May 2021 was conducted. All participants were included if they completed the pre-visit intake questionnaire before the rehabilitation process including the Athletic Identity Measurement Scale (AIMS), a self-report measure used to quantify athletic identity. All participants (N = 226) presented with anterior cruciate ligament injury and were reflective of the study region in race and ethnicity. Participants were evenly distributed between male and female and competed predominantly in a single sport (57.8%) at the school level (58.2%; **Table 1**).

Procedures

Data was collected from participants at the initial pre-operative presentation in clinic, defined as baseline. Age at presentation, sex, race, and ethnicity were demographic variables collected. Sport- and injury-related variables collected

TABLE 1 | Participant demographics and sport characteristics.

Variable	Group	N (%)
Sex	Female	115 (50.9)
	Male	111 (49.1)
Race	White	150 (66.7)
	Black or African American	52 (23.1)
	Non-White or Black	23 (10.2)
Ethnicity	Hispanic or Latino	64 (28.6)
	Non-Hispanic or Latino	160 (71.4)
Competition Level	School	82 (58.2)
	Select/Club	47 (33.3)
	College	3 (2.1)
	Other	9 (6.4)
Sport Participation	Single-Sport	93 (57.8)
	Multi-Sport	60 (37.3)

Non-White or Black may include Native American or Alaskan Native, Indian, Asian, or mixed race. Competition level was reported as the highest level achieved, with School as the lowest level and College as the highest level. Other competition levels may be described as recreational or non-competitive.

included competition level (school, club/select, college, or other), sport participation (single- or multi-sport athlete), sport participation volume (years in sport, days per week, weeks per year, weeks taken off per year), and recovery duration (days from surgery to return-to-sport clearance). PRO measures were also collected from the participant's intake form or surveys administered through the Outcome Based Electronic Research Database (OBERD; Universal Research Solution, LLC; Columbia, Missouri), an electronic PRO system validated in youth (Sabatino et al., 2019). PROs included the AIMS, the Hospital for Special Surgery Pediatric Functional Activity Brief Scale (HSS Pedi-FABS), the Pediatric International Knee Documentation Committee Subjective Form (Pedi-IKDC), the Anterior Cruciate Ligament-Return to Sport after Injury scale (ACL-RSI), and the Athletic Coping Skills Inventory-28 (ACSI-28).

Patient-Reported Outcome Measures

The AIMS is a validated measure for the young adult population that assesses athletic identity (Brewer et al., 1993), though it has not yet been validated for the youth population. The AIMS consists of 10 items rated on a Likert-type scale (1 = Strongly disagree, 7 = Strongly agree), and consists of three subscales including Social Identity (questions 1, 2, 3, and 7), Exclusivity (questions 4, 5, 6, and 9), and Negative Affectivity (questions 8 and 10). Social Identity is a measure of the extent of the athlete role dominating the social sphere; Exclusivity is a measure of the extent to which individuals both identify as athletes and do not identify with other roles; and Negative Affectivity is a measure of negative response to time away from sport. A higher score on the AIMS corresponds with a stronger identity as an athlete (Martin et al., 1997; Mitchell et al., 2021). Additionally, the AIMS may correlate with rehabilitation outcomes as described in Brewer et al. (2003) for individuals recovering from anterior cruciate ligament reconstruction (ACL-R).

The HSS Pedi-FABS is a functional activity scale developed to assess the participant's activity level in the month prior to completing it and is a validated measure for the pediatric population (age 10-18; Fabricant et al., 2013a,b). The scale consists of eight items assessing how often the respondent runs, cuts, decelerates, or pivots along with assessing duration, endurance, competition level, and supervision. The eight items are scored on a scale of 0-30, with a higher score indicating the respondent being more active.

An additional PRO validated in the pediatric population (age 10-18) with knee disorders is the Pedi-IKDC (Kocher et al., 2011). The Pedi-IKDC assesses symptoms, function, and sport activity through 15 items on a scale of 0-100, where a higher score represents a higher level of function and lower level of symptoms (Nasreddine et al., 2017).

The ACL-RSI is a 12-item PRO created to assess the psychological readiness to return to play in athletes following an ACL-R and has been found to be a good predictor of pre-injury level of participation (Langford et al., 2009; Ardern et al., 2013). A higher score on the ACL-RSI indicates a higher confidence in returning to sport on a scale of 0-100.

The ACSI-28 is a validated measure to assess an athlete's coping skills in seven domains: coachability, concentration, confidence and achievement motivation, coping, freedom from worrying, goal setting and mental preparation, and peaking under pressure (Webster et al., 2008). Each domain is evaluated on a scale of 0-12 and can be assessed independently; a total score can also be calculated ranging from 0-84. A higher score indicates greater strength in that domain and overall.

Statistical Analysis

Two groups were created to determine differences in demographic variables, sport characteristics, and psychosocial measures by total AIMS score. Specifically, participants with high AIMS scores ($AIMS_H$) were identified by a total score greater than 50, and low AIMS scores ($AIMS_L$) were identified by a total score less than 50. Given the limited literature on the AIMS in a youth population, a threshold value of 50 was selected based on the average total score computed from this cohort. This value also corresponds to that chosen in Padaki et al., which investigates a comparable mean age (2018). Descriptive statistics (means and standard deviations) were calculated for each AIMS question and total score across all participants, as well as between the two AIMS groups. Independent samples t-tests and ANOVAs were performed to identify differences between equally distributed groups (e.g., male vs. female; $AIMS_H$ vs $AIMS_L$). A conventional 0.05 level of significance was set for all statistical tests.

RESULTS

Across all participants, the average total AIMS score was 49.4 ± 11.9 out of 70 total points (seven points per question). The total cohort identified the least with the athlete role on questions 6 ('I need to participate in sport to feel good about myself') and 9 ('Sport is the only important thing in my life'). Alternatively, the cohort identified the most with the athlete role on questions 1 ('I consider myself an athlete'), 2 ('I have many goals related to sport'), and 3 ('Most of my friends are athletes'). Between $AIMS_H$ and $AIMS_L$ groups, question 6 exhibited the greatest deviation ($\sim$2.8 points; **Table 2**).

AIMS total score at baseline significantly differed by sex ($p = 0.002$). Specifically, males exhibited higher AIMS scores by 4.8 points, and the $AIMS_H$ group was found to be 58.5% male while the $AIMS_L$ group was 61.1% female. Additionally, no differences in AIMS total score were found between any of the remaining demographic or sport-specific groupings. Alternatively, participants in the $AIMS_H$ group reported $\sim$1.2 more 'years active in sport' ($p = 0.049$), a higher Pedi-FABS score ($p = 0.038$), and a lower ASCI-Coachability subscore ($p = 0.027$; **Table 3**). Notably, none of the three measures that exhibited AIMS group differences were found to significantly differ based on sex ($p > 0.05$).

DISCUSSION

The current study is the first of our knowledge examining the relationship between demographics, sport participation, psychosocial self-reported measures, and athletic identity in a pediatric sports medicine practice. While the primary outcome measure, the AIMS, has not been validated in children, studies of similar populations in adolescents or young adults have produced comparable AIMS values among participants. Padaki et al. (2018) found average AIMS scores of 52.8 – 57.5 (depending on the study subgroup) in their analysis of both youth and young adult athletes. McKay et al. (2013) found average AIMS scores of 55.72 ± 7.54 in their population of youth hockey players while studying athletic identity and fear avoidance. Similarly, Brewer et al. (2003) found average AIMS scores of 44.16 ± 9.98 in their study of competitive and recreational athletes of ages 14-47 years old, and Manuel et al. (2002) found average AIMS scores of 47.20 ± 9.78 in their study of athletes with ages 15-18 years and injuries of varying severity. With an average AIMS score of 49.4 ± 11.9 in the current study, the AIMS appears to be an effective indicator of athletic identity in children.

This study found that athletes in this population rated themselves the highest on questions assessing their identification with the athlete role as their social identity (questions 1, 2, and 3), and lowest on questions assessing the degree to which their self-worth is exclusively derived from their athletic role (questions 6 and 9). One interpretation of this result is that while participants strongly identified with their role as an athlete, it was not their sole source of self-esteem, indicating that they have other facets of their identity outside of the athlete role. This finding is consistent with the lack of differences in training volume and specialization by AIMS score. Moreover, it is encouraging since recent literature has shown that well-rounded youth are the most resilient and cope more effectively with injury and transitions from sport because being an athlete is not their only source of confidence (Christino et al., 2015).

The current study identified differences in AIMS scores based on sex which may be accounted for by the sporting environment they live in. Many sports are dominated by male or female participation, and gender continues to be an underexplored factor in ACL research despite consistently higher ACL injury rates in females (Parsons et al., 2021). Differences based on race or ethnicity, age, sport type, or sport competition level were not observed. The literature lacks consensus on how these measures relate to athletic identity, though age and athletic identity may positively correlate (Lamont-Mills and Christensen, 2006; Anderson et al., 2009, 2011; Proios et al., 2012; Babić et al., 2015; Şekeroğlu, 2017; Piatt et al., 2018; Edison et al., 2021; Rae and Jenkins, 2021). Furthermore, the population examined was treated at a specialty sports medicine treatment center, possibly explaining the unequal distribution of competition levels. Future work on athletic identity should be conducted in larger, more diverse samples.

While various studies have suggested that training hours correlate to athletic identity, data from this cohort did not reflect differences in AIMS scores based on hours per week, days per week, or weeks per year (Piatt et al., 2018; Quinaud et al., 2020). Traditionally, those who participate in more elite levels of sport are thought to have higher athletic identity (Ahmadabadi et al., 2014). However, as we observed no differences in competition level, it appears that participating at elite levels of sport alone does not correlate with high athletic identity, in this population. Notably, years active in

TABLE 2 | Baseline AIMS total score and individual question ratings (mean ± SD) for all participants and both AIMS groups.

AIMS Question	AIMS Score		
	$AIMS_{ALL}$	***$AIMS_L$***	***$AIMS_H$***
(1). I consider myself an athlete	6.5 ± 1.0	6.3 ± 1.3	6.8 ± 0.5
(2). I have many goals related to sport	5.9 ± 1.5	5.3 ± 1.8	6.5 ± 0.9
(3). Most of my friends are athletes	6.1 ± 1.4	5.6 ± 1.7	6.6 ± 0.8
(4). Sport is the most important part of my life	5.2 ± 1.8	4.1 ± 1.8	6.1 ± 1.2
(5). I spend more time thinking about sport than anything else	4.5 ± 1.9	3.3 ± 1.6	5.7 ± 1.3
(6). I need to participate in sport to feel good about myself	3.8 ± 2.3	2.3 ± 1.6	5.1 ± 1.9
(7). Other people see me mainly as an athlete	5.4 ± 1.8	4.4 ± 1.9	6.4 ± 1.0
(8). I feel bad about myself when I do poorly in sport	4.2 ± 2.2	3.1 ± 1.9	5.3 ± 1.8
(9). Sport is the only important thing in my life	2.8 ± 1.9	1.5 ± 0.9	3.9 ± 1.7
(10). I would be very depressed if I were injured and could not compete in sport	5.0 ± 2.2	3.7 ± 2.2	6.2 ± 1.3
Total Score	49.4 ± 11.9	39.4 ± 8.3	58.5 ± 5.7

TABLE 3 | Differences in continuous measures between $AIMS_H$ and $AIMS_L$ groups.

Variable	$AIMS_L$	$AIMS_H$	
Demographics/Participation Volume	***Mean ± SD***	***Mean ± SD***	***p-value***
Age	15.9 ± 2.1	15.9 ± 2.0	0.974
Recovery Duration	266.8 ± 99.8	273.7 ± 101.9	0.706
Years Active in Primary Sport	6.3 ± 3.8	7.5 ± 3.5	**0.049**
Hours per Week	9.7 ± 5.7	11.7 ± 11.9	0.213
Days per Week	4.5 ± 1.6	4.8 ± 2.0	0.243
Weeks per Year	30.3 ± 16.3	30.9 ± 15.8	0.834
Weeks Off per Year	10.1 ± 11.4	10.4 ± 11.5	0.919
Patient-Reported Outcome Measure			
Pedi-FABS	18.9 ± 9.8	22.2 ± 8.8	**0.038**
Pedi-IKDC	48.5 ± 21.1	48.5 ± 23.3	0.985
ACL-RSI	54.7 ± 26.8	53.6 ± 24.2	0.815
ACSI-Coachability	10.5 ± 1.7	9.7 ± 2.3	**0.027**
ACSI-Concentration	8.9 ± 2.1	8.5 ± 2.1	0.344
ACSI-Confidence and Achievement Motivation	9.6 ± 1.9	9.7 ± 1.9	0.913
ACSI-Coping	8.0 ± 2.4	7.3 ± 2.5	0.093
ACSI-Freedom from Worry	7.5 ± 2.8	7.1 ± 3.0	0.420
ACSI-Goal Setting and Mental Preparation	6.5 ± 2.8	7.2 ± 2.9	0.203
ACSI-Peaking under Pressure	7.6 ± 2.9	8.1 ± 2.7	0.283
ACSI-Total	56.2 ± 16.3	57.6 ± 10.3	0.561

Significance notated in bold.

their primary sport was significantly different between $AIMS_H$ and $AIMS_L$. It seems that athletic identity is less determined by current sport competition level and time commitment, and more determined by the amount of time sport has been present in the formative years of life. For those who have played their sport since early childhood, it may be more likely that their closest friendships and personal connections are related to the sport, regardless of their participation level. While sport specialization has generally been associated with athletic identity, we observed no difference between single-sport and multi-sport athletes (Renton et al., 2021).

Furthermore, we found that those in the higher AIMS group scored lower in ACSI-Coachability, which is one of many important characteristics for successful recovery. Despite an incentive to return to sport, injury may be more damaging to the psyche of individuals with greater athletic identity, resulting in their lack of openness to suggestions in recovery, i.e., coachability. This finding may also be derived from the competitive, and sometimes individualistic, nature of many athletes. Some athletes may suffer greater psychological impact after injury by disregarding outside intervention and/or keeping to themselves as a coping mechanism (Christino et al., 2015). Still, no other ACSI measures were different by AIMS groups. Given the lack of differences identified in the remaining ACSI measures, additional work is needed to further investigate the relationship between athletic identity, coping mechanisms, and fear avoidance as it may be significant to injury outcomes (Fischerauer et al., 2018).

No differences in readiness as measured by ACL-RSI were observed between $AIMS_H$ and $AIMS_L$ groups despite previous studies suggesting differences may exist (Ardern et al., 2014, 2016; Fischerauer et al., 2018). Similarly, subjective knee function as measured by Pedi-IKDC was not different between groups. Both measures' lack of differences is expected at recovery baseline as participants have not yet begun rehabilitation. However, activity as measured by Pedi-FABS scores did differ by AIMS group. Therefore, athletic identity and activity level may be correlated. While competition level did not see any differences in AIMS scores, activity level as measured by the Pedi-FABS could be a better representation of sport participation than competition level. Competition level may vary greatly between certain select/club level individuals – some may participate nationally at much higher intensity; others may participate in a local competitive league. Therefore, activity level should continue to be a focus of study with respect to athletic identity.

Limitations of the current study include a low sample size of certain demographic groups, specifically in race and ethnicity, and inconsistent sample sizes across variables. While some studies in young adults are available, this study was able to describe a population which had previously not been represented in the literature on athletic identity, and more specifically the AIMS. For this reason, a threshold of high and low AIMS scores has not been agreed upon in the literature. Thus, a threshold was chosen based on our cohort, which could be skewed given the region, type of treatment center, low sample size where testing was completed, and lack of healthy controls, though it appears consistent with other studies of similar populations. Additionally, by analyzing AIMS scores at baseline, only an initial assessment of the data was made in this study. Baseline in the current study is considered pre-rehabilitation; measurements at true baseline, or pre-injury, may yield different results. However, physicians and rehabilitation experts rarely see patients pre-injury, which suggests that the pre-rehabilitation baseline may be more clinically relevant.

The current study explores a population not previously studied with regards to athletic identity, sport participation, and psychosocial measures at a pediatric sports medicine practice. While youth athletes appear to be resilient, these results emphasize that they identify strongly with their role as an athlete and may suffer psychosocial consequences due to injury. Specifically, it was observed that sex, years active in sport, activity level, and coachability are important to consider at baseline before rehabilitation. Future work should validate the results in this study among a larger, more diverse population. Moreover, future studies should look to include assessments of the relationship between athletic identity, psychosocial factors, severity of diagnosis, and knee function over the course of recovery. Continuing research on such measures in athletic youths, thereby filling the current research gap, is essential to treat the debilitating effects of injury most effectively – both mentally and physically.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Texas Southwestern Institutional Review Board. Written informed consent from the participants' legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

JM, SU, and ES contributed to conception and design of the study. JM and SU organized the database. SU performed the statistical analysis. JM wrote the first draft of the manuscript. HW and SU wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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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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OPINION
published: 20 June 2022
doi: 10.3389/fpsyg.2022.936140

Naturalistic Decision-Making in Sport: How Current Advances Into Recognition Primed Decision Model Offer Insights for Future Research in Sport Settings?

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Keywords: decision-making, intuition, recognition, expertise, sports

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

Received: *04 May 2022*
Accepted: *31 May 2022*
Published: *20 June 2022*

Citation:
Bossard C, Kérivel T, Dugény S, Bagot P, Fontaine T and Kermarrec G (2022) Naturalistic Decision-Making in Sport: How Current Advances Into Recognition Primed Decision Model Offer Insights for Future Research in Sport Settings? Front. Psychol. 13:936140. doi: 10.3389/fpsyg.2022.936140

INTRODUCTION

The Naturalistic Decision-Making (NDM) approach (Klein, 2008, 2015; Hallé Petiot et al., 2021) is an alternative to the cognitivist approach (i.e., decision-making viewed as a rationalistic linear information process) and to the ecological-dynamic approach (i.e., decision-making viewed as behavioral adaptation to environmental constraints). NDM researchers have discovered that decision makers in natural settings rely heavily on intuition. Experts use their experiences to focus their perceptions onto salient features, to recognize situations as typical, and to choose the most appropriate option. The Recognition Primed-Decision (RPD) model (Klein et al., 2010) postulates that experts' decision-making is a recognition process and suggests three levels of experiencing a situation: (i) simple match (recognize a situation and associate the first adequate option), (ii) diagnose the situation (faced with a non-familiar situation and need time to adapt a typical action), (iii) evaluate a course of action (simulate the relevance of the first option through mental visualization).

The RPD model has been applied in sport settings as rapid decision-making is essential for sporting expertise (for a review see, Macquet, 2020). Numerous qualitative studies have investigated the recognition processes in Australian Football officials (Neville et al., 2017), soccer referees (Mascarenhas et al., 2009), badminton players (Macquet and Fleurance, 2007), volleyball players (Macquet, 2009; Fortin-Guichard et al., 2021), soccer players (Bossard, 2010; Kermarrec and Bossard, 2014), ice hockey players (Bossard et al., 2010; Mulligan et al., 2012), handball goalkeepers (Le Menn et al., 2019), basket-ball players (Macquet and Kragba, 2015), judo athletes (Macquet and Lacouchie, 2017), karate athlete (Milazzo and Fournier, 2015), rugby coaches (Collins et al., 2016; Ashford et al., 2020), and sport adventure coaches (Collins and Collins, 2016).

Thus, this consistent empirical evidence obtained through investigation during naturalistic games strengthen the assumption that experts' decision-making in sport is based on their intuition. Nevertheless, some paradoxes remain and call for future investigation: six key points could be promising avenues of research.

INTERPLAY BETWEEN INTUITIVE AND ANALYTIC DECISIONS

According to Macquet (2020) literature review of the RPD model in sport, 60–81% of the experts' decisions were classified as intuitive, using simple matching, about 13–28% of the experts' decisions were related to diagnosis, and about 3–24% were related to evaluating a course of action. Time pressure in the game situation is invoked to explain the predominance of intuition. Nevertheless, some issues suggest that the role of the decision-maker and the context in which he is embedded could affect the recognition mechanism. Investigating a handball goalkeeper's decision-making (Le Menn et al., 2019) or soccer defenders' decision-making (Kermarrec and Bossard, 2014), researchers found that when athletes were far from the ball, they had more time for mental simulation and diagnosing the development of possible situations. Furthermore, rugby coaches' decision-making was less subject to less time pressure than athletes, so that deliberative or analytic decision were frequent (Collins et al., 2016).

Taken together, these outcomes suggest that decision-making in a sport setting may take place on a continuum between intuitive and analytical processes (Kahneman and Klein, 2009). In this sense, integrated theoretical models of decision-making have recently been proposed for athletes (Ashford et al., 2021a,b; Hallé Petiot et al., 2021), referees (Kittel et al., 2021a; Samuel et al., 2021) and coaches (Collins et al., 2016; Richards et al., 2017). There is a lack of consistent empirical evidence in a sport setting for establishing the continuum from intuitive to analytical decision-making. Furthermore, based on outcomes in other research fields (e.g., Calabretta et al., 2017), future studies in sport should examine the interplay between intuitive and analytic decision-making in athletes, coaches and referees.

VISUAL SEARCH STRATEGIES AND INTUITION

Moreover, NDM studies also brought information on the relevant cues decision-makers take into account when embedded in the course of an action. As pointed by Macquet (2020), relevant cues were context-specific and were mostly concerned with visual perception. Today the field of visual search strategies is fertile among athletes (Vater et al., 2019; Krabben et al., 2022), referees (Luis del Campo et al., 2018; Moore et al., 2019) or coaches (Robertson et al., 2018; Mitchell et al., 2020). New methodological designs need to be proposed in order to study the visual information that is prioritized by experts in situation recognition and intuitive decisions in more ecological conditions (i.e., naturalistic conditions). Research designs that immerse participants in environments close to real sports settings with video filmed with a 360° camera (Musculus et al., 2021) or with virtual reality (Mascret et al., 2022) seem to be a very promising methodological avenue. Thus, an original contribution from RPD for sports may consist of studying decision-making in naturalistic sports games settings, providing empirical evidence on the way experts make intuitive decision and use very few cues to support ongoing decisions and actions.

INTUITIVE DECISION-MAKING AND CREATIVITY

Although it is common to associate intuition and creativity, a clear link between them has not been adequately established in sports sciences. Quite the contrary: previous empirical research on IDM in sports settings showed that expert athletes choose their preferred "first option" most of time (in 80% of the decisions made), so they could be considered as non-creative. Nevertheless, the role of intuition in creativity should not be neglected as it is often reported to be a core component of the idea generation process (Pétervári et al., 2016). Sports researchers recently took into consideration this assumption when experimenting team sports programs aiming to develop players' creativity and adaptive behaviors (e.g., Coutinho et al., 2016). Furthermore, the relation between creativity and perceptual and cognitive processes was recently examined in experimental decision-making studies. Firstly, creative decision-making and visual search behavior were investigated in skilled soccer players (Roca et al., 2018; Roca and Ford, 2020). The results showed that most-creative players employed a broader attentional focus including more fixations of shorter duration and toward more informative locations of the display compared with least-creative players. Secondly, Klatt et al. (2019) examined the relation between creativity and IDM in two studies—one involving coaches and one involving soccer players—using video footage of real soccer matches. Results indicate a positive correlation between a player's creativity score and the quality of the first generated option for the whole sample. Even if the topics of those studies were not the recognition primed-decision processes, the results confirm insights about the relationship between IDM and creativity. If more creative players and coaches tend to maintain a broader attentional focus in a realistic sport setting, they should also be more sensitive to recognizing many salient cues.

IDM AND THE ROLE OF EMOTIONS

In recent decades, interest in the links between decision-making processes and emotions has grown (George and Dane, 2016). Emotions have often been considered as biases or hindrances to decision-making, especially in cognitive approaches studying athletes, referees and coaches (Tenenbaum et al., 2013). More recently, emotions have begun to emerge as resources for decision-making in a variety of models (e.g., Affect as information approaches, Appraisal tendency framework, Affect infusion model). The NDM approach also considers emotion as a potential resource. Empirical studies on this issue have focused on managers in companies (Sayegh et al., 2004), bank agents (Lipshitz and Shulimovitz, 2007), emergency doctors (Coget and Keller, 2010), film directors (Coget et al., 2011) or aircraft maintenance engineers (Naweed and Kingshott, 2019). These studies highlight the diverse roles of emotions in intuitive processes involved in complex, uncertain and time-pressured situations, supporting the theoretical assumptions of the NDM approach (Mosier and Fischer, 2010). To our knowledge, no study has shown the role of emotions in IDM in the context of sport. According to several empirical studies cited above and conducted through the NDM framework, situationally-induced emotions in a real-world context, namely "integral affects" (Mosier and Fischer, 2010) could play different roles in sports decision-making. Taken together these issues suggest further investigation of the role of emotion in the RPD model in a naturalistic decision-making perspective. Three hypotheses concerning these roles can thus be proposed: (1) expert pattern matching and intuitive decisions often could be guided by an affective appraisal of the situation, (2) emotional responses such as discomfort could motivate individuals to look for more sources of information to make a more deliberative decision, and (3) if the mental simulation of the potential evolution of the situation induces discomfort, individuals might be tempted to opt for another option.

THE DEVELOPMENT OF IDM

The development of sports experts' IDM underlies two types of research questions corresponding to two distinct promising research avenues: (1) How does the development of IDM contribute to the development of sports expertise? (2) Which training programs could enhance IDM in sport?

NDM researchers in sport science have typically focused on IDM in experts, but the development of intuition and its contribution to the development of expertise still lacks empirical evidence (Martindale and Collins, 2013). Researchers from other fields have provided insights by considering the interaction between intuition and deliberation and how their use might lead to "skilled intuition" (Kahneman and Klein, 2009). Baylor (2001) argued for the possibility that the development of intuition follows a U-shaped progression where immature intuitions start at a relatively high level and then decrease when decisions become more analytic, and later increases with available intuitions. Bangert et al. (2014) hypothesized that musicians deliberately explore and test interpretative options, perhaps guided in their search by intuitive pattern recognition. Future studies in a sports context should examine the development of intuition to understand how athletes, coaches and referees become experts.

Proposals for training decision-making in sport are mainly based on a perceptual-cognitive approach to decision-making both for athletes (Hadlow et al., 2018), referees (Kittel et al., 2021b) and coaches (Richards et al., 2017). Proposals for training IDM based on NDM approach are less common and still lack empirical evidence. The research work of Kittel et al. (2021b) and the recommendations for introducing reflective practices with referees could be an interesting way to improve IDM. Future interventional studies could be set up based on programs dedicated to improving IDM in order to test their effects.

IDM IN TEAMS

Previous sections in this paper argued to revisit the RPD model (Macquet, 2020). Several studies presented below are in sports contexts and especially in team sports. Thus, in naturalistic approaches there is a need to connect decision-making and team cognition research in both athletes (Steiner et al., 2017; Bourbousson et al., 2019), referees (Boyer et al., 2020) and coaches (Richards et al., 2017). Three perspectives could be investigated. Firstly, Kermarrec and Bossard (2014) showed that decision-making in defensive phases in soccer need to be coordinated. Results support the fact that decision-making is connected to shared cues in the situation. Secondly, as this paper argued for the investigation of the development of IDM to understand how athletes become experts, there is a need to understand the development of collective intuition at team level (Kérivel et al., 2021). Future studies could use recent theoretical advances (Akinci and Sadler-Smith, 2019) to understand links between collective intuition and decision-making. Thirdly, this paper suggests that IDM could be influenced by emotions. From a team perspective, shared emotion could also influence team naturalistic decision-making and the interpersonal coordination between team members (Van Hoorebeke, 2006; Tamminen and Crocker, 2013). Future studies may examine the influence of emotions on sharing and decision-making processes in team sports, coaching teams, and referee teams.

CONCLUSION

The use of the NDM approach, and more specifically of the RPD model is relatively recent in the field of sport. The growing number of empirical studies has confirmed its relevance for the understanding and enrichment of decision-making in sports settings. Previous results also invite researchers to question the model and its relations with six other determinants of expertise (analytical decisions, visual search strategies, creativity, emotions, development and team coordination), usually studied separately from IDM in both athletes, referees and coaches. In conclusion, the six avenues of research to revisit the RPD model, as suggested in this article, require innovative research methods to capture the complexity of IDM in naturalistic sports contexts.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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frontiers | Frontiers in Psychology

REVIEW
published: 24 June 2022
doi: 10.3389/fpsyg.2022.930025

Individual vs. Team Sport Failure—Similarities, Differences, and Current Developments

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OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *27 April 2022*
Accepted: *09 June 2022*
Published: *24 June 2022*

Citation:
Wergin VV, Mallett CJ and Beckmann J (2022) Individual vs. Team Sport Failure—Similarities, Differences, and Current Developments. Front. Psychol. 13:930025. doi: 10.3389/fpsyg.2022.930025

The construct of "choking under pressure" is concerned with the phenomenon of unexpected, sudden, and significant declines in individual athletes' performances in important situations and has received empirical attention in the field of sport psychology. Although a number of theories about the reasons for the occurrence of choking under pressure exist and several intervention approaches have been developed, underlying mechanisms of choking are still under debate and the effectiveness of existing interventions remains contested. These sudden performance declines also occur in team sport. "Collective sport team collapse," which describes the situation when an entire sport team underperforms significantly within an important competitive situation, has received less empirical attention, in comparison to individual choking research. While there are a few studies that have investigated causes of collective team collapse, understandably, there has been limited empirical investigation of preventative and intervention strategies. Although the two constructs appear to share several similar characteristics and mechanisms, research has not yet examined the conceptual, theoretical, empirical, and practical links between choking under pressure and collective sport team collapse. In this review article, we seek to examine these similarities and differences and identify new ways of thinking about future interventions. Furthermore, current empirical understandings in the field of choking under pressure and collective sport team collapse are presented and the most effective intervention approaches for both constructs are introduced. On the basis of this examination, we modestly make some initial recommendations for sport psychological practitioners and future research.

Keywords: choking under pressure, performing under pressure, collective team collapse, team dynamics, team choking

THE CONSTRUCTS OF CHOKING UNDER PRESSURE AND COLLECTIVE TEAM COLLAPSE

Performing when it matters the most is certainly important to athletes and may not only determine victory or defeat, but impact athletes' careers, like the one of golfer Jean Van de Velde, whose dramatic underperformance in the final round of The Open Championship is ranked among the top performance failures in sport history (Siegel, 2011). While some athletes perform to their expected standards or on rare occasions surpass previous expectations, others tend to show impaired performances in pressure situations, which usually include important competitions and/or the presence of a large audience (e.g., Wallace et al., 2005). When professional track and field athletes stumble in the Olympics or elite soccer players miss the game deciding penalty shot in the finals of the World Championships, they likely experience "choking under pressure". Initially defined by Baumeister (1984) as "performance decrements under circumstances that increase the importance of good or improved performance" (p. 610), several definitions of choking under pressure have developed; however, no global definition exists (Buszard et al., 2013; Jackson, 2013; Mesagno and Hill, 2013).

Individual athletes choking under pressure has been of interest to researchers, pracitioners, and the public, but teams (as a collective) have also suddenly and significantly underperformed in important games. This frequently takes the form of a sudden collapse of the performance and has therefore been described as "team collapse" (Apitzsch, 2006; Wergin et al., 2018). A famous example of collective team collapse is the 1–7 loss of the Brazilian team against Germany in the semi-finals of the 2014 FIFA World Cup in front of their home audience (Filho, 2021). An applied analysis showed that Brazil started the game with a regular performance, which was disrupted by the first goal scored by Germany, leading to a series of further four goals scored in the next 15 min of the game (Filho, 2021). Even though the similarities between individual choking and team collapse might appear to be obvious, surprisingly, the two strands of research have remained relatively unconnected to date. The present article attempts to integrate research on choking under pressure and collective team collapse to identify mutual characteristics to inform future interventions.

Since both constructs are based on different literature, we first present research on choking under pressure in individual sports as well as on existing interventions. Thereafter we introduce literature on collective team collapse and potential interventions. Finally, we discuss links and differences between the two constructs to advance insights and develop interventions to circumvent performance failure on both the individual and team level.

CHOKING UNDER PRESSURE

Research on choking under pressure has largely focused on explaining the phenomenon of dramatic underperformances in pressure situations and their underlying mechanisms. Generally, literature distinguishes between attention-based models and self-presentation models of choking under pressure (e.g., Mesagno et al., 2011; Mesagno and Beckmann, 2017), which are outlined in the following sections.

Attention-Based Models of Choking Under Pressure

Despite the lack of a consensus in definition, performance anxiety appears to play a key role in causing athletes to underperform or "choke" under pressure (e.g., Mesagno and Hill, 2013; Mesagno and Beckmann, 2017) and has been referred to in several theories. According to attention-based theories of choking under pressure, anxiety in important performative situations leads the athlete to either focus so intensely on the movement that the movement cannot be executed regularly anymore (i.e., increased self-focus) or evokes distracting thoughts in the athlete, causing a lack of attention (i.e., distraction) (Baumeister, 1984; Beilock and Carr, 2001). An increased self-focus is typically accompanied by a shift in focus from sport relevant information to internal cues, such as the execution of the movement or an inner feeling of the body. The athlete may closely monitor the movement execution (Beilock and Carr, 2001) or try to consciously control certain movement components (Masters, 1992), equally leading to a disruption of the movement and causing choking under pressure.

Distraction, on the other hand, is characterized by interrupting myriad thoughts, which are not related to the competitive situation and might, for example, be related to possible outcomes of the competition or past experiences in previous tournaments (Eysenck et al., 2007; Oudejans et al., 2011; Englert and Oudejans, 2014). Eysenck and Calvo (1992) argue that this is likely due to an increase in anxiety during the performance situation, leading to an increased activity in the working memory, which reduces the capacity to focus on task-relevant stimuli. A further explanation is that anxiety increases athletes' attention to threat-related stimuli, such as the consequences of a possible failure (Eysenck et al., 2007), which not only potentially shifts an athlete's attention but also might contribute to additional anxiety.

Self-Presentation Models of Choking Under Pressure

Theories based on self-presentation as main cause of choking assume that we are always aiming at presenting ourselves to others in a favorable way, creating desirable impressions, and prohibiting the development of undesirable impressions (Leary and Kowalski, 1990; Leary, 1992). This is especially true for athletes with a strong need to be perceived as skilled and talented by coaches and audience, as this may have a positive impact on selection decisions and therefore on their career (Prapavessis et al., 2004). The striving for an ideal self-presentation does, however, have the potential to increase anxiety in athletes (Wilson and Eklund, 1998) and lead to choking in important performance situations. Mesagno et al. (2011) argue that certain personality traits increase this anxiety about self-presentation in athletes. An athlete who is worried about the judgment of coaches or audience, for example, is likely experiencing higher levels of anxiety and a higher susceptibility to choking under pressure. In accordance with this, self-confidence and self-consciousness are further crucial factors to consider when performing in front of an audience (Wang et al., 2004).

CURRENT DEVELOPMENTS AND INTERVENTIONS IN CHOKING

Several prevention and intervention strategies for choking under pressure have been developed. As anxiety has been shown to play a major role in causing choking under pressure (Mesagno and Beckmann, 2017), many of the strategies focus on reducing the feeling of anxiety or its outcomes, such as attentional problems or an increase in arousal. Hence, we present the following most popular interventions for choking under pressure in regard to their intended goal of attentional regulation, change of appraisal, or arousal regulation, which is in line with Gross' (2015) initiation for emotion regulation.

Attention Regulation

Building upon the assumptions of self-focus models, interventions aiming at reduced conscious control and a reduced application of explicit knowledge have been developed. Masters (2000) used an analogous motor learning approach to limit explicit knowledge and foster the use of implicit knowledge in athletes, which applies biomechanical metaphors to teach complex actions like, for example, drawing a triangle with the bat for a correct execution of a top spin hit in table tennis. In several experiments, Masters (2000) showed that the performance of individuals who had applied the implicit learning strategy was more resilient to stress and pressure than the performance of individuals who had applied explicit learning. Similar results were achieved by Liao and Masters (2001) in table tennis players and by Lam et al. (2009) in basketball players. These experiments provide an approach allowing athletes to recall their performance in an automated and unconscious way, making them less susceptible to choking under pressure.

Contrary to struggling with an increased self-focus, athletes may experience difficulties focusing on the task and feel distracted by task-irrelevant thoughts. An intervention that has shown to help athletes adjust their focus are pre-performance routines. These routines mainly aim at helping athletes focus on the task, prohibiting a distraction by undesired thoughts (Mesagno and Beckmann, 2017). Pre-performance routines typically consist of a sequence of thoughts and actions (e.g., cognitive preparation, deep breathing, or cue words) directed toward the task to be performed and have been shown to stabilizes athletes' performance in pressure situations (e.g., Mesagno and Mullane-Grant, 2010).

Pre-performance routines can easily be combined with strategic self-talk (Galanis et al., 2021), which may further involve an application of rhythms and/or music. German basketball player Dirk Nowitzki for example acknowledged that he hummed David Hasselhoff's song "Looking for Freedom" to get himself ready for conducting a free-throw (Pollakoff, 2015). This technique has been scientifically investigated and shown to be especially effective when the music matched the characteristics of the movement (e.g., Pates et al., 2003; Mesagno et al., 2009). Another technique to be applied prior to the execution of performance is quiet eye (Vickers, 2007), where an athlete visually fixates a target prior to executing the movement. Quiet eye can be combined with other pre-performance routines such as breathing or thinking (Mesagno et al., 2019).

A further technique that has shown to support athletes to enter a mental state of automatism is imagery or visualization. Imagining the movement prior to its conduction has been shown to protect athletes from choking (e.g., Hill et al., 2011; Hill and Shaw, 2013). The imagery task should be adjusted to the skill level of the athlete, for example by having novice athletes imagine the movement from a third-person perspective, which is easier, while more advanced athletes may use the more effective but also more difficult first-person perspective (Krawietz, 2013).

Change in Appraisal

As discussed above, choking under pressure and unhelpful emotions, such as athlete anxiety, go hand in hand, as anxiety usually drives underperformance in important sports situations (Mesagno and Beckmann, 2017). It is therefore unsurprising, that several intervention strategies have targeted unhelpful emotions and include emotion regulation strategies. One of these strategies is cognitive reappraisal, involving a change of the evaluation of the negative stimulus or the situation that initially caused the emotion (Gross, 2002). An athlete could for example evaluate the competitive situation as a chance to play some good sport and show his or her own skills rather than perceiving it as a threat of potentially losing the game. A further variation of this technique is cognitive reframing, which refers to the identification of negative thoughts and a goal-oriented restructuring of these thoughts into positive ones. Cognitive reappraisal has been shown to help athletes cope with pressure (Balk et al., 2013).

Supplementary to re-evaluating the situation or reframing thoughts, athletes may use the strategy of relativization of the situation (Jermann et al., 2006). This strategy aims at putting the current pressure situation into a broader perspective. A tennis match can be perceived as a threat for the individual player, but compared to other, rationally more threatening situations, it is perceived as less significant. Within this strategy, watching news and putting the own sport in the perspective of being "just a sport" are common tactics.

Arousal Regulation

Apart from interventions addressing attention and emotion, a variety of interventions aiming at the regulation of athletes' arousal have been developed. One of the best-established interventions targeting the downregulation of athletes' arousal is resilience or simulation training. This training technique is often applied by coaches and typically includes a pressure or anxiety induction during practice in order to get athletes used to a certain level of stress and increase their resilience to this stress (e.g., Beilock and Carr, 2001; Oudejans and Pijpers, 2009, 2010; Mesagno et al., 2015; Fletcher and Sarkar, 2016).

Further strategies that similarly target a downregulation of arousal in athletes are typical relaxation methods, including for example deep breathing, mindfulness, or hypnotic practices (e.g., Parnabas et al., 2014; Scott-Hamilton et al., 2016). While the original versions of these techniques are rather difficult to apply in sports, several adaptions have been made, essentially shortening the techniques to allow for an application in the field. Breathing techniques usually focus on a prolonged exhalation and can easily be adapted to sports, for example, by letting athletes count during their breathing and increasing the amount of counted numbers during the exhaling phase. Breathing techniques can further be combined with mindfulness practices, which add a focus on other bodily sensations or on visual and auditive stimuli to the routine.

A further technique that has been shown to effectively reduce anxiety and other unhelpful emotions, and therefore may be used to interfere with choking, is embodiment. Embodiment aims at changing the mental state of an athlete through body posture, physical expression, and body tension (Gallagher, 2005). The technique is based on the principles of muscles sending information about posture back to the brain, influencing feelings, information processing, and motivation. Since athletes can consciously control their body posture, embodiment can be applied as a tool to make oneself feel less anxious and more self-confident. Another embodiment technique is the left-hand dynamic handgrip (Beckmann et al., 2013). Using this approach, right-handed athletes clench their left hand dynamically for 10–15 s, which has been shown to produce a state of cortical relaxation (Cross-Villasana et al., 2015), reducing anxiety and the experience of choking under pressure in athletes (e.g., Beckmann et al., 2013, 2021).

Taken together, existing research on choking under pressure has mainly focused on self-presentation and attention-based models and designed interventions tailored to those theories. We illustrated existing interventions in the light of Gross' (2015) theory of emotion regulation, as all of them target different stages of the emotion development process, indicating that a holistic approach to emotion regulation may be key to the development of intervention strategies.

COLLECTIVE SPORT TEAM COLLAPSE

Although it is assumed most team sport athletes are familiar with the phenomenon of an entire team suddenly underperforming simultaneously, it empirically remains poorly understood. Similar to choking under pressure, collective sport team collapse appears to happen during important games or tournaments, when the perceived pressure on the team is high (Apitzsch, 2006) and has been defined as "a sudden, collective, and extreme underperformance of a team within a competition, which is triggered by a critical situation that interferes with the team's interplay, a loss of control of the game, and ultimately the inability of the team to regain their previous performance level within the game" (Wergin et al., 2018, p. 5). Initial studies on collective sport team collapse showed that rather than being evoked by single causes, team collapse can be understood as a process and occurs as a result of a cascade of causes, whereby a critical event on the court typically triggers the collapse (Wergin et al., 2018, 2019).

While certain antecedents, such as a lack of attention, overconfidence about winning the game, and/or an insufficient level of experience or preparation may function as risk factors increasing the likelihood of a team collapse, the occurrence of a critical event on court can be seen as the starting point of the collapse. Such critical events may include an accumulation of mistakes in the own team, points scored by the opponent team, game interruptions (e.g., due to injury of a player), key players of the team suddenly choking, or referee decisions made against the team. These critical events change dynamics within the team on an emotional, cognitive, and behavioral level.

On an individual cognitive level, major impacts of the critical event include the perception of increased pressure, an insecurity about the situation, and despair in a way that athletes do not know what to do (Wergin et al., 2018). Furthermore, Wergin et al. (2019) found players to switch from a goal-oriented thinking to a defensive and prevention-oriented thinking, including worrying about failing the expectations that others held about their team's performance. On a team level, athletes suffer from a perceived lack of accountability among team members. Players refuse to take responsibility for game situations (e.g., win the ball), as they do not want to be held responsible for the failure of the team (Wergin et al., 2018). They also perceive team members to individualize and to be playing on their own rather than as a collective, potentially leading to an actionist atmosphere within the team, causing individual players to try to score by physical force (Wergin et al., 2019).

Examining the emotional changes in players and the team, an increase in unhelpful emotions, especially in anxiety and anger (Wergin et al., 2018) as well as frustration (Wergin et al., 2019) can be observed in players. Interestingly, these emotions transfer from one player to another (Wergin et al., 2018, 2019), a process that has been referred to as emotional contagion (Hatfield et al., 1994) and that has been investigated in a number of studies in sport (e.g., Totterdell, 2000; Moll et al., 2010) as well as in organizational settings (e.g., Kelly and Barsade, 2001; Barsade, 2002). It can thus occur, that a player experiences the mood from a teammate without having participated in the initial emotion evoking game situation. Through this process, negative atmospheres can spread rapidly within a team facing a collective team collapse.

Changes on a behavioral level include decreased performance as well as either a cautious or a more hectic play of individual team members (Wergin et al., 2018). Furthermore, an immobility or "freezing" of players on the court has been observed as a result of increased levels of anxiety (Wergin et al., 2019). On a team level, behavioral outcomes of the collapse can become even more severe. Communication between team members decreases significantly, while externalizing blame to other team members increases (Wergin et al., 2018), eventually leading to a collapse of the main strategic system of play. The mistakes and failures occurring on an individual level appear to also transfer between team members, causing an accumulation of mistakes in the team (Wergin et al., 2018, 2019).

These changes in a team's dynamics evoke further failure by the players of the team, again impacting emotions, cognition, and behavior, which maintains the underperformance of the team in a vicious cycle that seems difficult to arrest. Hereby, especially social factors, involving processes between teammates, such as the transfer of unhelpful emotions from one player to another, appear to hinder the team from recovering their performance and constitute a unique facet of collective team collapse.

CURRENT DEVELOPMENTS AND POTENTIAL INTERVENTIONS IN TEAM COLLAPSE

Wergin et al. (2020) were able to initially record collective team collapse events in field hockey teams using GPS trackers. They found teams who indicated to have suffered from a team collapse during their games to be running significantly less in these team collapse games compared to games they had lost without experiencing a team collapse. Furthermore, Wergin and colleagues showed that negative affect increased significantly in teams experiencing a team collapse compared to the same teams losing a game without collapsing. One may assume that positive affect would similarly decrease significantly in team collapse games compared to lost games, but this was not the case. Especially negative affect appeared to impact athletes' performance and it was assumed that, in accordance with the findings of Wergin et al. (2018), negative affect is associated with negative thoughts in athletes and prohibits them from returning to their initial performance level. Besides causing rumination, the regulation of negative affect likely affects performance as well. A relationship between affect regulation and performance has been shown in various studies (e.g., Muraven et al., 1998; Schmeichel et al., 2003; Wagstaff, 2014; Haehl et al., 2022). Wagstaff (2014) for example showed that a cycling time trial was performed worse by participants who had to regulate their affect prior to their trial compared to a control group.

Building upon this assumption that negative affect and its regulation foster the ongoing underperformance of a team, more effective affect regulation strategies may be key to the development of prevention and intervention strategies. *Depersonalization* is a concept within the Social Identity Theory (Tajfel, 1978; Tajfel and Turner, 1979) that suggests that when our sense of self is fully immersed in the social group or team, we behave prototypically consistent with the group and share a social identity ("we-ness"), whereby we derive our self-concept from the group. The identification with the group impacts our affect and behavior, as the group takes on affective significance for us (Tajfel, 1978). Group based emotions are experienced by the individuals within the group, who now act as group members rather than as individuals (Goldenberg et al., 2016). Additionally, members of the group can experience collective emotions simultaneously, when encountering a specific event together, like for example competitions or games. These collective emotions are a form of group-based emotions and can be understood as a "synchronous convergence in affective responding across individuals" (von Scheve and Ismer, 2013, p. 406). Specifically, winning and losing constitute ultimate stressors for sports teams, evoking individual as well as collective affect in response (Tamminen et al., 2016b). Critical events, posing the beginning of the actual collapse, can be understood as similar situations, in which teams have to deal with problems and are similarly associated with a loss of the game. Such critical situations can therefore evoke negative affect and a transfer of this affect between team members (Wergin et al., 2018, 2019).

Thus, individual as well as interpersonal affect regulation strategies could support a team in enhancing its performance, when facing negative (collective) affect and affect transfer processes in a team collapse situation. Affect regulation refers to "attempts to influence emotions, in ourselves and others" (McRae and Gross, 2020) and typically relates to performance (Wagstaff, 2014). Sport psychological research has, however, mainly investigated individual strategies of affect regulation. Niven (2017) provides a conceptual framework of affect regulation that takes the possibility of interpersonal affect regulation into account. Within this framework she differentiates between intrinsic and extrinsic affect-improving and affect-worsening regulation. While intrinsic strategies to improve one's own affect can for example consist of positive thinking or seeking social support, intrinsic affect-worsening strategies could include negative thinking or cynicism. Strategies aiming at improving others' affect are listening to them and their problems and providing helpful advice. Strategies to worsen others' affect could be acting annoyed or pointing out their deficits. Niven's (2017) framework has been associated with athletes' autonomous motivation and commitment (Tamminen et al., 2016a) as well as with team anxiety and goal achievement (Tamminen et al., 2021) and team success (Tamminen et al., 2019). As to date, no prevention or intervention strategies to counter collective sport team collapse have been invented, individual and interpersonal affect regulation and potentially a combination of both present a promising approach for future research and practice aiming at preventing collective team collapse.

In sum, research on collective team collapse indicates the importance of emotion regulation on both the individual and the team level. Intervention strategies targeting individual and interpersonal emotion regulation could be useful in stabilizing performance of individual athletes as well as their collective team performance.

RELATION BETWEEN CHOKING AND TEAM COLLAPSE

The mechanisms underlying choking under pressure and collective team collapse as well as the interventions developed to date show both differences and similarities between the two constructs. Existing research has investigated choking as an underperformance of individual athletes at a certain point in time, while collective team collapse has been investigated from a broader perspective, whereby causes and mechanisms have been described from a broader perspective as well.

However, the two main characteristics of choking, which comprise the severe underperformance of an athlete in an important, competitive situation, carrying a significant amount of pressure, are similarly part of collective team collapse. Individual choking can occur as part of the team collapse, for example, when a key player chokes, and pressure has been found to be both an antecedent of team collapse as well as an outcome that maintains the team's underperformance, as a team usually experiences increased levels of pressure after falling behind due to a performance collapse (Wergin et al., 2018, 2019).

Furthermore, some of the specific mechanisms underlying choking under pressure have been identified in collective team collapse as well. The attentional issues that athletes typically report when facing a choking situation (e.g., Baumeister, 1984; Masters, 1992; Beilock and Carr, 2001) have also been found in collective team collapse (Apitzsch, 2006; Wergin et al., 2018, 2019), where they appear in the form of an antecedent. These attentional antecedents are mainly characterized by a lack of attention of teammates, which is similar to the distraction theory in choking literature, while an increased self-focus has not been related to team collapse so far.

Beyond that, and in accordance with self-presentation theory (Leary and Kowalski, 1990; Leary, 1992), both constructs are characterized by a fear of failure and a fear of negative evaluation by others. Anxiety, which has been described as a detrimental factor for performance recall (e.g., Kleine, 1990; Smith and Smoll, 1990; Mesagno and Beckmann, 2017; Ehrlenspiel and Mesagno, 2021) has similarly been shown to play an important role in driving collective sport team collapse (Wergin et al., 2018, 2019). While this anxiety often leads to a direct performance decrease in individual athletes as well as to a further increased anxiety level after the failure, fear of failure in sports teams can be contagious within a team. Anxiety in team sports has been shown to impact the team in terms of player responsibility or lack thereof. Specifically, there seems to be a reluctance and aversion to take responsibility for addressing the collapse, because no player wants to be held responsible for the team losing the game. This typically leads to a cautious playing behavior of team members, which makes it even easier for the opponent to score (Wergin et al., 2018, 2019).

Apart from anxiety, other negative emotions and cognitions cause players to get caught in the vicious cycle of underperformance and decreases their chances to recover their performance. In particular, the feelings of anger and frustration play major roles in choking under pressure (e.g., Gucciardi et al., 2010) and team collapse (Apitzsch, 2006; Wergin et al., 2018, 2019, 2020). When athletes experience these emotions, they often and subsequently feel desperate and overwhelmed, which often causes a conscious or unconscious surrender of the game. Within a team these emotions can easily accumulate and make the situation spiral downward further.

At first sight, collective sport team collapse may appear like a team form of choking under pressure, as many of the individual processes fostering choking can also be found in team players during a team collapse event. However, choking and team collapse differ in many other processes and mechanisms. Wergin et al. (2018) argue that due to the many social processes that are involved in the establishment of a team collapse, such as the transfer of negative emotions and cognitions and the interactions between players (e.g., blaming each other for failure), there is more to team collapse than the simultaneous choking of various players at the same time. This assumption is supported by the fact that the choking of one or more individual players in a team does not necessarily cause a team collapse. It appears to be crucial for the development of a team collapse, who the choking players are and in which situation they choke (Wergin et al., 2018, 2019). It may occur that one individual player choking, especially a key player, causes failure and choking in other players, but this social process of performance contagion that is accompanied by the transfer of emotions and behaviors, is unique to collective team collapse. The most interesting question is, which specific mechanisms are leading to these emotional, cognitive, and behavioral transfer processes, as those mechanisms can be understood as the engine keeping a team collapse running. Thus, gaining a better understanding of these processes is key to the development of prevention and intervention strategies.

Even though choking under pressure and team collapse can be understood as constructs describing two distinct phenomena and have been investigated independently to date, there are some factors, which should be considered in the promotion of future research. Research on choking under pressure could benefit from addressing determining factors that emerged in the research on team collapse. In research on choking under pressure, the view of choking as a process, including a sequence of causes or triggers, has largely been neglected. While initial theories of choking under pressure, such as self-presentation theory or self-focus and distraction theory, may well explain the underperformance in sports where a single task is performed, such as shooting sports or jumps in gymnastics, existing theories do not consider the continuous choking of an athlete throughout performances consisting of multiple tasks, performed over a longer period of time, like for example in individual racket sports (e.g., tennis, badminton, table tennis) or choreography-based sports (e.g., dancing, figure skating, rhythmic gymnastics). In these sports, where a variety of tasks are performed for a certain duration, choking under pressure may occur in form of a dynamic self-reinforcing process. Initial underperformances can evoke further negative thoughts and emotions, which again impact performance and create even more pressure due to the initial underperformance. Choking in these sports can be understood as a process similar to collective team collapse. Therefore, some of the underlying mechanisms of collective team collapse could also play a role in fostering choking under pressure in individual sports.

Furthermore, although individual sports are performed by one person, social factors relating to other persons surrounding the athlete and their impact on the athlete, like in team collapse situations, might also be considered. While social interactions in team collapse situations, such as blaming each other for failure, mainly occur between players of a team, coaches, the audience, opponents, and potentially parents of youth athletes may exert a similar influence on athletes performing individual sports. An example may be provided by athletes choking when their coach enters the competition arena. Choking in this case is likely triggered by social interactions between coach and athlete during both practices and competitions. Also, system characteristics are worthy of investigation to examine social communications, such as finger pointing and increasing blaming behaviors from spectators and coaches.

Additionally, it should be remembered that athletes in many individual sports also have teammates. Even though they may not always perform simultaneously, but after another, like for example in relay sports, interpersonal behaviors of these teammates matter. It is equally important for individual athletes, that their teammates support them and interact with them in a positive way when facing a challenging situation. While showing negative emotions or behaviors toward a teammate in relay sports may not produce a team collapse, negative interactions, such as finger pointing, may cause an individual performer to choke.

Therefore, considering both choking mechanisms in team collapse as well as team collapse mechanisms in choking is important for gaining a better understanding of both constructs and being able to intervene on both the individual and team level. Integrating knowledge we have of both constructs, like for example viewing choking from a process perspective, can support the development of new holistic interventions.

PRACTICAL IMPLICATIONS

It is important for coaches and sport psychological practitioners working with teams to take both the individual player and the entire team into account, when trying to mitigate against potential team collapse. On an individual level, similar interventions to those that have been shown to be effective for individual choking can be used to educate players of a team about self-regulation strategies to stabilize performance. Hereby, strategies involving individual attention regulation may be of limited benefit, as many aim at gaining back an automated movement, which is not helpful in regular game situations in team sport (except for penalty shootings etc.). Thus, the major focus should be based on techniques aiming at a change of cognitive appraisals and those involving arousal regulation, because being able to change perspective and evaluate the situation differently as well as being able to downregulate one's own negative affect is a first step in recovering oneself prior to helping teammates and in prohibiting a transfer of the own affect to others (Tamminen and Crocker, 2013).

On a team level, several different strategies might be considered. Firstly, it is important to make a team aware of the possibility of a team collapse and prepare them for the occurrence of such an event (Wergin et al., 2018, 2019). As a specific strategy of preparation, a solution focused approach developed by Maechel et al. (2021) on the principles of athlete leadership, may be applied. The team development program aims at improving a team's performance through different processes. Initially, a team is asked about what is going well in their team from their perception, before working out which processes could be improved. In a final step, the team develops and agrees on specific steps to be taken, in order to reach their goals for improvement in a democratic and empowering process. This tool can easily be adapted to prepare a team for a collective team collapse situation. The players would have to reflect on what they did well in a team collapse situation of the past, what they could to better, and how they want to achieve this in a future team collapse situation.

Secondly, teams should work on emotion regulation strategies, as emotion regulation has been shown to improve team performance (Tamminen and Crocker, 2013). Since the development of interpersonal emotion regulation strategies is still in its infancy, teams could focus on basic implementations, such as, discussing their individual preferences for interactions with teammates when facing serious underperformance situations. If teammates know how to motivate and emotionally and socially support each other without taking the risk of escalating negative emotions, team members already have tools to conquer the emotional mechanisms of team collapse. Thus, team communication training could be an important tool to stabilize performance promoting adaptive affect within a team.

Thirdly, as a team collapse event is often accompanied by a decrease of communication in the team, interventions could focus on maintaining the quality and quantity of communication in difficult game situations (Wergin et al., 2018). Certain players could, for example, take responsibility to communicate changes of play or new strategies during team collapse events. Such roles and responsibilities should be determined well ahead of the game or even the season. A discussion about responsibilities and tasks can also be combined with the previously described preparation strategies of Maechel et al. (2021) or discussions about emotion regulation preferences.

Lastly, research has shown that a team culture, in which teammates are blamed for failure, decreases team cohesion and is of disadvantage in difficult game situations (e.g., Wergin et al., 2018, 2019), while a culture of no blame is typically related to team resilience (Morgan et al., 2013). Specific rules of behavior among each other should be mutually developed by team members and fostered by coaches and practitioners. As in modern business companies, a supporting team culture with appreciation as core value and emphasis on individual ownership should be lived. This would also apply to athletes in individual sports.

SUMMARY AND OUTLOOK

Choking under pressure and collective sport team collapse are two distinct constructs explaining performance failure on different levels, which share certain characteristics, but also differ considerably. Team collapse includes many dynamic interpersonal processes, such as the transfer of negative affect between team members or negative behaviors directed at each other, which again impact the further course of the team collapse. These social processes can be seen as key points for the development of interventions that breach the dynamics of a team collapse and therefore recover a team's performance. It can be assumed that these factors also affect performance in individual sports to some degree and should, therefore, be taken into account in the prevention of choking under pressure in these sports.

Research on choking as well as on team collapse should embrace the development and especially the testing of intervention strategies. While many interventions in the area of choking exist, not all of the interventions used by practitioners have been investigated scientifically. New interventions should view choking as a process and target not only the prevention of the specific choke but also dealing with failure to prevent further chokes and a negative downward spiral over the course of a game or tournament. The development of team collapse interventions is still in its infancy and many more studies on the construct as well as on prevention and intervention strategies are needed.

AUTHOR CONTRIBUTIONS

VW wrote the first draft of the manuscript. CM and JB wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

FUNDING

This work was supported by the Senior Excellence Faculty of the Technical University of Munich (TUM).

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frontiers | Frontiers in Psychology

OPINION
published: 06 July 2022
doi: 10.3389/fpsyg.2022.926419

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What If Leisure Time Activities Were a Solution for Athletes' Long-Term Development and Health?

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Keywords: adolescent athletes, leisure, performance, recovery, sustainable practice

INTRODUCTION

Adolescents who wish to pursue a career as a high-performance athlete are expected to be engaged in a sport specialization process. In this way, they have to adopt an intense and specific focus on one sport and exclude others. Although youth sports participation has been linked to numerous physical, psychological and social benefits, it has also been associated with negative outcomes such as low self-esteem, aggressive behaviors or eating disorders (Fraser-Thomas et al., 2005). The modern integrated approach underlines that the youth athletes system is organized around three main subsystems (i.e., family, team and environmental subsystems), which are interrelated and impact athletes' development and practice (Dorsch et al., 2022).

Then, in addition to the constraints and goals of the sport, the life and career of modern adolescent athletes are characterized, in many countries, by the requirement to undertake education alongside their sports training. Studies that have investigated dual career (DC) in student-athletes have shown that this population experiences high demands across athletic and non-athletic levels of development (Brown et al., 2015). These studies also highlighted that student-athletes have to balance their time and energy to fulfill their commitments in different life areas, bringing out the time management challenge between time constraints and leisure time, organizational capacity and long-term development (Stambulova et al., 2021).

Sport and educational commitments are typically associated with entrance into academies or clubs with high prestige. In order to facilitate athletes' participation and achievement in education and sports programs, many countries set up Sports and Academic Training Centers (SATCs). SATCs aim to offer athletes all the resources they need from an academic and sports point of view. However, despite the SATCs support, it has been recently highlighted that the sports specialization process still predisposes adolescent athletes to social isolation, poor academic performance, emotional disturbances, intense and chronic stress states, lack of proactive recovery strategies, decreased family time, and burnout (Brenner et al., 2019). In response to these health concerns and behaviors, several health organizations have proposed guidelines and position statements to guide parents and practitioners toward best practices for managing young athletes. A recent literature review (Herman et al., 2022) highlighted that the most common recommendations endorsed the following concepts: "monitor athlete wellbeing," "youth athletes need access to well trained, quality coaches," "multi-sport participation," "limit early organized participation and/or training," and "parents require awareness of training, coaching, and best practices." However, Herman et al.'s study (Herman et al., 2022) highlighted that: (a) the level of evidence provided to support a given recommendation varied significantly; (b) the level of detail and the consistency of terms used throughout the results were typically low, and (c) recommendations were frequently made without reference to potential outcome measures or specific strategies that could be used for practical implementation in the community.

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

Received: *22 April 2022*
Accepted: *21 June 2022*
Published: *06 July 2022*

Citation:
Vacher P, Sondt N, Levillain G, Bossard C, Prost M and Bernier M (2022) What If Leisure Time Activities Were a Solution for Athletes' Long-Term Development and Health? Front. Psychol. 13:926419. doi: 10.3389/fpsyg.2022.926419

According to the recent literature, there is a lack of applied strategies that may help student-athletes to cope with the various stressors and constraints related to the sport specialization period of their careers, that could lead to dysfunctional states. Beyond the positive and negative aspects of early sport specialization for long term development, performance, health and sport participation (LaPrade et al., 2016), we argued that it would be a fundamental perspective in sports science to validate interventional protocols in this way. Considering the specificity of adolescent student-athletes that are engaged in sport specialization, it appears that these athletes are exposed to the increased sport and educational constraints in their lifestyle, leading to time pressure. This time pressure is expressed as a lack of time for physical, psychological and own needs recovery, which is a psychological condition and burnout significant risk factor (Sorkkila et al., 2020). In this line, we assume that adolescence is a pivotal period for athletes' development because most mental health disorders occur in late adolescence and early adulthood, as well as identity formation and individuation (Sutcliffe and Greenberger, 2020). Especially, adolescent athletes that have to commit in sport specialization are an at-risk population in the way that they may develop a unique identity (i.e., athlete identity), which is risky when things go wrong as an athlete (injuries, setbacks, etc.), leading adolescents' foundation to be shaken (Champ et al., 2020). Therefore, investigating new strategies that consider the problem of time pressure and the need for leisure activities to ensure adolescents' functional development and maturation is of crucial interest for a long-term performance perspective and a sustainable sports practice.

LEISURE ACTIVITIES APPROACH

While physical and mental recovery in sport have received increasing attention in research and practice the past decades (Kellmann, 2010), we notice that leisure activities is underexamined in sports science, perhaps because of the culture of effort, work and surpassing oneself attached to sport performance.

Leisure is defined as how one's spends their free time, and is considered as being the "*principal driving force underpinning the human desire to render life meaningful… or to give it the sense of passion, pleasure and purpose*" (Blackshaw, 2017). These voluntary non-work activities (Hills and Argyle, 1998) are engaged in for enjoyment and encompass actions such as: taking part in hobbies; participating in arts; taking educational classes; reading; socializing; shopping; listening to music; engaging in libraries or culture; cooperating in community, neighborhood, or tenants' groups; and participating in social clubs (Fancourt et al., 2021). Accordingly, thousands of studies have shown a relationship between leisure engagement and both physical and mental health (e.g., mental health: prevention and management of mental illnesses such as depression, anxiety, stress; physical health: chronic pain, frailty, coronary heart disease and disability) (see Hills and Argyle, 1998 for a review).

According to the Multi-level Leisure Mechanisms Framework (Fancourt et al., 2021), leisure activities are complex interventions in that they contain individual and group level components and outcomes (Craig et al., 2013). To date, over 600 potential mechanisms of action by which leisure activities might affect health have been identified and categorized into psychological, biological, social and behavioral processes (Fancourt et al., 2021). Some of these mechanisms operate at the micro-level (i.e., affect individuals or tiny groups). In contrast, others operate at the meso-level (i.e., affect larger groups, communities, and institutions) or at the macro-level (i.e., affect societies and cultures at large). To quickly summarize the literature, some of these mechanisms can be directly activated by leisure management and engagement (and will have an immediate effect on health), while others are part of more complex indirect pathways and will affect health from a long-term perspective (Fancourt et al., 2021). Then, considering leisure activities requests to keep in mind that (a) no leisure activity will activate just one causal mechanism (Rogers, 2008); (b) leisure activities effects are the result of the interaction of multiple different mechanisms (Preiser et al., 2018); leisure activities interventions mechanisms are non-linear and involve feedback loops and recursive causality (Rogers, 2008; Preiser et al., 2018). Finally, leisure mechanisms only make sense when they are considered from a dynamic systems perspective (Kernick, 2006), rather than on static states and protocols (Fancourt et al., 2021).

DISCUSSION

Despite the central role of leisure activities for individual development and health, we failed to find studies in sports science that investigates applied protocols in athletes. In the general population, organized leisure-time activities (OLTA) have been identified as allowing the individual strengths of adolescents to be aligned with developmental assets (Bowers et al., 2014). OLTA represents a wide range of activities taking place during leisure time outside the regular school curriculum (Bohnert et al., 2010). These activities can be characterized as having a structure with defined rules and goals, being supervised by adults, having a regular schedule and putting emphasis on skill-building (Larson, 2000; Mahoney et al., 2005). Literature has shown associations between OLTA and relevant healthy youth development factors in adolescents (Bohnert et al., 2010; Farb and Matjasko, 2012). OLTA recognized benefits in the general population cover protections against risk behaviors, reduction in substance abuse consumption, delinquency, or bullying of others (Farb and Matjasko, 2012). It has also been shown that OLTA may be a way to channel some stress-reduction efforts (Darling, 2005) and negate the need for stabilization of one's social position through risk behaviors (Viau and Poulin, 2015; Viau et al., 2015), giving social support for identity-related exploration. Finally, studies have shown that one's participation in OLTA leads to an increase in his/her experience to higher levels of intrinsic motivation and challenge at the same time (Hansen et al., 2010), promoting the development of initiative, identity formation, and the building of teamwork skills and social capital (Hansen et al., 2003).

All of this seems to link OLTA to healthy developmental outcomes (Farb and Matjasko, 2012), which may be of key interest for adolescent student-athletes. This suggests that specific leisure mechanisms and applied protocols should be investigated in student-athletes, mainly based on longitudinal protocols and ecological conditions. For example, it would be interesting to investigate how applied protocols based on OLTA recommendations could help adolescent athletes preserve their recovery-stress states around real training seasons. An important challenge for these protocols will be to carefully manage how "adolescents" activities will be organized. Indeed, it has been shown that adolescents' participation in organized activities has protective effects while overscheduling induces major concerns in this population (Badura et al., 2015). In this line, a quantitative and qualitative approach should be relevant in order to individualize interventions and to take into account the key 'athletes' biopsychosocial aspects in a systemic approach. This research field may benefit from the extensive literature that exists on the general and disease population. It may help develop specific models and applied strategies to ensure a long-term sustainable practice and psychological/physical/social development of adolescent athletes.

AUTHOR CONTRIBUTIONS

PV, NS, GL, CB, MP, and MB were involved in the manuscript preparation. All authors contributed to the article and approved the submitted version.

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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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frontiers | Frontiers in Psychology

TYPE Opinion
PUBLISHED 17 August 2022
DOI 10.3389/fpsyg.2022.959599

Check for updates

OPEN ACCESS

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

RECEIVED 01 June 2022
ACCEPTED 01 August 2022
PUBLISHED 17 August 2022

CITATION
Zahno S and van der Kamp J (2022) When insights based on ecological and cognitive theories to movement science converge—The case of creativity in sports.
Front. Psychol. 13:959599.
doi: 10.3389/fpsyg.2022.959599

When insights based on ecological and cognitive theories to movement science converge—The case of creativity in sports

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KEYWORDS

motor skill, motor learning, motor performance, creative actions, variability, adaptability

In sports, athletes strive for highly efficient and functional actions that make them competitive in their discipline. These actions are considered creative when they are also unforeseen, for example because they are new or rare in a specific situation. Sports practitioners increasingly recognize that creative actions provide a key competitive advantage (Glynn, 2013). In football, for example, in an attacking phase of play, a skilfully executed backheel pass can take the opponent by surprise and disrupt a well-organized defense to ultimately decide the game. Creative actions thus are not only highly functional but are also recognized as unconventional performances that make people marvel at sports. Accordingly, both sports practitioners and scientists are increasingly interested in understanding how creative actions come about and how they can be promoted. However, despite its intuitive appeal, creativity is a challenging topic; not the least because of the conceptual ambiguity surrounding it.

In recent years, we have independently conducted research into creativity from contrasting theoretical frameworks in movement science, ecological psychology (Orth et al., 2017; Withagen and van der Kamp, 2018) and cognitive theories of motor behavior (Zahno and Hossner, 2020). Interestingly, our approaches have resulted in converging conceptualizations of creativity in sports. This convergence may be surprising as ecological and cognitive theories to motor behavior are traditionally perceived to fiercely contest each other—a debate known as the "motor-action controversy" (Meijer and Roth, 1988). In this paper, we aim to highlight three converging insights on creativity in sports. We will further discuss how these insights contrast the current dominant approach to creativity and what they imply for ideas and practices that are widespread in sports. Finally, we reflect on the implications for the "motor-action controversy".

Before focussing on creativity, we provide a brief background on the "motor-action controversy". In the 1980s, ecological psychologists confronted the traditional "motor" theory, which held that movement control is mainly top-down determined by centrally stored representations (e.g., motor programs) that *pre*-scribe the details of the to-be produced movement pattern (e.g., Schmidt, 1975). Instead, ecological psychologists, using concepts of dynamic systems theory, proposed an "action" theory, where movement behavior is described in terms of lawful information-movement couplings (Warren, 1988). These lawful relationships emerge (or self-organize) within an individual's search to satisfy the dynamic constraints of the constituting person-environment relationship (Newell, 1986). In this view, control is as much a feature of the environment as of the person. Accordingly, learning entails an increased adaptive flexibility; that is, the emergence of movement pattern variability to maintain or expand a stable person-environment relationship (Davids et al., 2012). Learning is thus associated with degeneracy; meaning that similar stable movement behaviors can be achieved with different movement patterns. However, since the heydays of the "motor-action controversy", fundamental conceptual re-orientations have been observed *within* cognitive or "motor" theories (see Hossner et al., 2020). Most notably, the idea of centrally stored motor programs that prescribe detailed movement patterns has been abandoned (Todorov and Jordan, 2002). Instead, James' (1890) ideomotor principle has been reinstated, expressing that behavior is controlled in terms of the anticipated effects (i.e., predicted perceptual consequences) of one's own actions (Prinz, 1997). Accordingly, in the theory of optimal feedback control (Todorov and Jordan, 2002), behavioral control is conceptualized as self-initiated transitions from current (perceived) situations to desired (perceived) situations. Thereby, it is a core feature of the theory that *not* each and every state dimension needs to be controlled. Rather, in the unfolding situation, motor commands are generated only if they essentially contribute to the maintenance or achievement of the desired situation. Learning, in this view, is thus conceptualized, *not* as acquiring centrally represented movement patterns, but as refining and expanding links between current (perceived) situations and the (perceived) effects in the environment of one's own actions. In cognitive theories, these links are conceptualized as forward models (Franklin and Wolpert, 2011). Or put differently, learning is also associated with degeneracy within this cognitive framework.

It is common for both sports practitioners and scientists to attribute creative actions, such as the backheel pass in football, to an athlete's ability to generate creative ideas (e.g., Memmert, 2015). This attribution has been adopted from traditional approaches in creativity research that are based on the concept of divergent thinking (Guilford, 1967). Divergent thinking tasks assess a participant's ability to generate multiple alternative ideas in response to a problem. Translating this into sports, this ability is assumed to enable the athlete to produce creative actions across a diverse range of sport-specific situations, and perhaps even beyond (Memmert and Roca, 2019). A corollary conjecture is that athletes can improve creativity with training programs dedicated to enhancing the ability to generate creative ideas (e.g., Memmert, 2021). Our recent research challenges this common view. We rather conceive creative actions as emerging from adaptations to momentary constraints, and thus as grounded in sensorimotor skill (Orth et al., 2017; Zahno and Hossner, 2020). Rather than enabled by a general, context-independent capacity for creativity that is active *before* the action, we argue that the "creative" of creative action arises *in* action and is thus always embedded in a sport-specific situation. But what do we understand as creative actions? This question leads to our first insight.

Insight I: The "creative" in creative action reflects a judgement rather than being a property of the action or athlete

Creative actions refer to actions that are both functional (i.e., support task success) and considered novel, non-conventional (i.e., beyond typical standards) or rare in a particular context (cf. Runco and Jaeger, 2012). This implies that the "creative" in creative actions (or of creativity) is, in essence, an evaluative judgment of functional actions in terms of novelty, unconventionality, or rareness in one particular situation and not necessarily in another. This judgement of an action as being "creative" is inherently relative. It compares one action within a defined historical and social situation with other actions in the same situation (Westmeyer, 1998; Csikszentmihalyi, 1999). Most basically, this can be described as the statistical rareness of the action in that situation (Simonton, 2003; Caso and van der Kamp, 2020). Two consequences can be derived from this insight: (1) The same action can be highly creative in one context while being ordinary in another, just as the same action can be entirely novel at one point in time and become standard repertoire of a domain ever after. In other words, the "creative" in creative actions is not an inherent property of an action but is always defined relative to the situation in which it arises (Zahno and Hossner, 2020). Accordingly, we have shown in football that some environments (i.e., small-sided games) invite more and different creative actions than others (i.e., 11-aside) (Caso and van der Kamp, 2020). (2) The "creative" in creative action does not refer to some magical source or ability that forms the action. It is not something that athletes "possess" or "acquire". Importantly, however, this does not imply that the athlete should be considered irrelevant. To the contrary, creative actions are grounded in the athlete's skill or adaptive flexibility (Ericsson, 1999). This brings us to the second insight.

Insight II: Creative actions are grounded in athletes' sensorimotor skill rather than in an ability to generate ideas

Skilled athletes show a large, more variable movement repertoire. This enhances adaptive flexibility, allowing them to produce actions in ways that less skilled players cannot. Consequently, such actions are more likely to be statistically rare and thus creative. Accordingly, to promote creative actions, coaches should foster athletes' sensorimotor skill rather than their ability to generate ideas. We have tested this hypothesis in a recent field-based experiment in elite youth football (Zahno and Hossner, in press). Players who participated in football-specific divergent thinking training did indeed improve their capacity for creative idea generation. However, these improvements did not induce more creative actions on-field. In contrast, players who received motor skill training not only improved in functionality but performed more creative actions on-field. Beyond, in beginner football, Orangi et al. (2021) showed that a variable motor skill training, which aimed to channel players' search for adaptive movement patterns, resulted in more variable and creative movement behaviors than motor skill training that prescribed desired movement patterns. These results suggest that creative actions are not based on players' ability to generate ideas *per se*, but rather on what they *can* do *in* the situation. Consistent with both ecological and cognitive-ideomotor theories, this underlines that creative actions are grounded in sensorimotor skill, and particularly in the skilled athletes' adaptive flexibility to solve unfolding situations in multiple ways. This adaptiveness brings the person-environment relation to the forefront and leads to our third insight.

Insight III: Creative actions are relational rather than a product of the individual alone

Dick Fosbury's revolutionary high jump technique won him the Olympics in 1968. A critical constraint in the creation of this novel technique was the replacement of the sand pit by crash mats in high-jump competitions. This shifted the boundaries of the task space for high jumping, allowing Fosbury to explore new task solutions such as landing on his back. Interestingly, Debbie Brill, a young athlete from Canada independently discovered the same technique around the same time. This shows that the invention of the Fosbury Flop cannot be understood as originating from Dick Fosbury solely but is co-constituted by and an adaption to a changing sport-specific context. Creative actions are thus always defined across the person-environment relationship. Consequently, creative actions cannot be trained as a de-contextualized ability. Rather, when designing practice, coaches should take sport-specific situations as a starting point and invite athletes to explore different ways of solving the situation; for example, by manipulating task constraints to make athletes adapt to changing constraints and thereby enhance variability of actions (Hristovski et al., 2011; Orth et al., 2017). Empirically, recent studies in football (Caso and van der Kamp, 2020; Orangi et al., 2021) and boxing (Orth et al., 2019) have confirmed that inducing a large variability of actions enhances the chance for creative actions to emerge.

To conclude: Our approaches to creativity in sports originate from traditionally opposed theoretical perspectives but converge in how they explicate creative actions and derive implications for practice. Creative actions are grounded in sensorimotor skill, wherein a large and variable movement repertoire associated with adaptive flexibility increases the likelihood for actions to arise that are recognized as "creative". For sports practice, this suggests that creative actions are best promoted by motor skill training, especially when designing sport-specific environments that invite athletes to safely explore, discover and invent a rich repertoire of actions to solve movement problems (see e.g., Rasmussen et al., 2019).

This convergence, obviously, does not dissolve the "motor-action controversy". Fundamental differences between "motor" and "action" theories remain. Arguably, the one that stands out is the ontology of internal mechanisms in "motor" theories vs. the sufficiency of the information-movement coupling in "action" theories for explaining movement behavior. From an applied perspective, however, instead of debating the veracity of the two theories, it seems more fruitful to recognize that, in the end, they are both models that aim to understand the reality of human movement behavior. And if distinct theories converge to a similar understanding, then perhaps we have increased our grip on that reality. Surely, this strengthens confidence in the practical recommendations that are derived—in this case, for sports. Intriguingly, and consistent with our current thinking, it may exactly be the variability in theoretical approaches that increases the likelihood of new conceptualizations that extend our understanding in a field of study. In this respect, we must cherish the "motor-action controversy", rather than solving or—worse—ignoring it. That is, the interactions between the "motor" and "action" theories during the debate were an important impetus for theoretical developments. We thus believe that it is crucial to revive the cross talk between the theories particularly since open discussion and in-depth conceptual analysis of where the (sub)fields of the study of human movement behavior converge can benefit science as well as the practice of sports and beyond.

Author contributions

SZ and JK contributed to conceptualization, background research, and draft work. All authors contributed to the article and approved the submitted version.

Funding

Open access funding was provided by University Of Bern.

Acknowledgments

We would like to thank Ernst-Joachim Hossner for valuable comments on the paper as well as Catherine Haber for proofreading the manuscript.

Conflict of interest

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

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TYPE Perspective
PUBLISHED 22 August 2022
DOI 10.3389/fpsyg.2022.929487

Current concepts and practical applications for recovery, growth, and peak performance following significant athletic injury

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OPEN ACCESS

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

RECEIVED 26 April 2022
ACCEPTED 29 July 2022
PUBLISHED 22 August 2022

CITATION
Brooks TJ, Bradstreet TC and Partridge JA (2022) Current concepts and practical applications for recovery, growth, and peak performance following significant athletic injury. *Front. Psychol.* 13:929487.
doi: 10.3389/fpsyg.2022.929487

For decades, physicians, athletic trainers, and other health care professionals have worked to standardize the recovery process following injury to enhance patient outcomes and to help set appropriate goals for return to competition. Traditionally, these efforts have focused primarily on physical and/or physiological aspects of healing with little consideration for psychological aspects. Concurrently, mental health professionals who work with athletes have developed strategies to enhance performance and minimize negative influences of mental aspects of recovery while promoting approaches that include mental as well as physical recovery. Several strategies have emerged that further encourage a multi-faceted and interdisciplinary approach when helping injured patients return to participation. While important in a healthy population, the practical applications of these strategies are likely more critical for an athlete working through the recovery process with an ultimate goal of returning to competition. Despite these realities, both practical experience and a dearth of literature point to the traditional athletic healthcare providers' common focus on physical aspects of recovery and psychological professionals' focus primarily on mental aspects has resulted in sub-optimal outcomes compared to the likely benefits of an integrated approach. This article is intended to characterize current concepts in the fields of sport psychology and mental health concerning the importance of mental aspects of recovery in returning to play. Next, the authors will examine how modern theories can influence practice and discuss how these strategies can be effectively integrated and leveraged to enhance recovery and the athlete's enjoyment of the rehabilitation and ultimately restoration process.

KEYWORDS
rehabilitation, recovery, growth, interprofessional care, behavioral medicine, athlete psychology

Introduction

Competitive athletics—particularly at the elite/international level—are frequently viewed by the masses as the very zenith of the human experience. After all, in order for an athlete to achieve or even approach unprecedented levels of human performance, it is likely that all aspects of their preparation have been analyzed, optimized, and analyzed again. Frequently, this involves training and recovery, nutrition, coaching, and tactical aspects of performance. Sport coaches and strength & conditioning specialists develop highly specific plans with the singular goal of maximizing athletic performance. If any aspect of function could be improved, it is likely that the athlete and/or their coaching staff would attempt to leverage that potential to maximum effect.

However, such an approach has traditionally demonstrated a glaring blind spot. Specifically, issues concerning mental health and psychological strategies to enhance performance have historically been lacking relative to their physical and physiological counterparts. The underpinnings of this difference are multivariate and complex, however, most would suggest that (at least until recently) the "warrior mentality" so prevalent in competitive sport has served to stigmatize seeking help for mental health and psychological concerns by the athlete (Glick et al., 2009; Rice et al., 2016). As Olympic medalist Sasha Cohen has adeptly summarized, in the highly competitive realm of elite athletic competition, "You need to show the world that you are strong, so if you were to say, 'oh, I have mental issues,' that just cracks the facade of trying to show the world that you're impervious," (Rapkin, 2020).

Against this backdrop of historic and systemic resistance to mental and behavioral health care in sport, the medical needs of competitive athletes have often been addressed primarily from a physical rather than more global approach (including mental health care) for decades. At the same time, the pursuit of maximal performance also comes at the price of increased risk of injury. Whether suffered during training or competition, acute or chronic in nature, and managed through more conservative or surgical means, physical injury from sport holds the potential to be a major negative life event. In addition to pain and compromised/lost performance, injuries can also contribute to poor mental health (Gouttebarge et al., 2019; Chang et al., 2020). Unfortunately, given the typical resistance to mental health care even in the healthy state, many athletes may avoid seeking mental health care as a part of the recovery process for physical injury.

To further confound matters, sports medicine professionals (including physicians, athletic trainers and physical therapists) who are commonly present throughout the injury evaluation, care, and rehabilitation process have traditionally lacked the formal academic or clinical preparation in order to appropriately manage mental health concerns in their patients. Such issues are usually considered outside the scope of practice for their respective professions, making referral the only possible intervention for providers of affected patients. However, with the overwhelming majority of sport governing bodies, professional teams, and athletics programs only recently beginning to provide the necessary funding to provide ready access to trained mental health professionals, the typical sports medicine provider is ill prepared and lacking the outside resources to provide or coordinate care to help the injured athlete through this critical aspect of recovery.

Thankfully, over the course of the past two decades, this reality has slowly started to change for the better. Sport organizations and institutions have begun to recognize the critically important nature of a more holistic approach to care, particularly with high profile athletes such as Simone Biles and Naomi Osaka speaking candidly about their experiences with mental health professionals in the recent past. In order to positively impact overall health of athletes through the purposeful inclusion of mental health professionals, administrators and decision makers have allocated the necessary resources to support these efforts. This article has been written to inform the reader regarding the history, current state, and the future of this contemporary interprofessional and more holistic approach to athletic health care. It is hoped that over time, the pioneering programs of the past decade in particular will become the norm rather than the exception.

Historical perspectives

The traditional model of athletic health care

While competitive athletics have existed globally since the times of the ancient Greeks and Romans, health care for athletes has varied widely over the centuries. Historical accounts of well-known medical pioneers such as Hippocrates and Galen date some of the earliest known care rendered specifically to athletes as early as 400 BC (Prentice, 2021). However, with the fall of the Roman Empire just prior to 400 AD, interest in sport—and concurrently, the medical needs of athletes—fell dramatically. Not until the Renaissance beginning in the 14th century did interest in sport begin to return.

With the resurgence of sport came a renewed need to provide medical care for athletes. The profession of athletic training, an allied health profession composed of credentialled professionals who function primarily to prevent, recognize, and manage injuries to athletes and the physically active, was first organized to provide for the emerging medical needs of collegiate athletes in the United States in the early 1900s (Ebel, 1999). At the same time, other health care professions have also grown, with many further developing subspecialities specific to rendering care specifically to athletes and the physically active. "Sports medicine" has historically been used as an umbrella term that includes any medical professional who works specifically with athletes, including physicians, physician assistants, nurses and nurse practitioners, athletic trainers, physical therapists, occupational therapists, chiropractors, and other related care givers.

Despite significant growth in the field and the dramatic increase in medical services and coverage for athletes—particularly at the collegiate, professional, and secondary school levels—most efforts since the earliest development of sports medicine have been focused on addressing physical aspects of injury with little to no attention to mental and behavioral aspects of care. While true in all aspects of care, the purpose of this article is to specifically consider the rehabilitation process following significant injury. For many athletes, weeks or even months are spent on physical restoration. However, what is commonly lacking is a more holistic approach to healing that includes mental health care.

As sports medicine has grown over the decades, other professions have emerged as critical components of a seemingly ever-growing team. Strength and conditioning specialists, data analysts, sports nutritionists, and sport psychologists are frequently employed by many professional and upper-level collegiate programs. This more specialized interprofessional model not only ensures each member functions legally within the respective profession's scope of practice, it also provides for a better level of care than would be possible under more antiquated models of delivery.

Current and emerging models of integrated athletic health care

The following depicts three of the most common approaches to providing mental health and sport psychology services to competitive athletes following significant injury. It is important to note that all models are not exclusively employed following injury and can be highly valuable in assisting with a variety of peak performance concerns. While some programs continue to offer little to no care (typically due to budget concerns), thankfully, the prevalence of such arrangements is on the decline.

In-house programs

Although the costliest alternative, many sport organizations or departments have dedicated full-time positions to one or more sport psychologists to render care to athletes. The potential upside to such programming is tremendous. Athletes can be provided with greater depth and breadth of care and coordination between other members of the sports medicine team is greatly facilitated. Some have noted that the in-house model is important simply because it signals a culture that embraces the importance of mental health, and at the same time serves to de-stigmatize commonly cited resistance to seeking care (Chew and Thompson, 2014). Particularly with respect to the rehabilitating athlete, this model promises to best facilitate communication and interprofessional teamwork among all members of the sports medicine team.

On the other hand, this model does present a few drawbacks. Cost is certainly a concern, however, others have cited limited professional support, high demands on a single clinician, limited resources beyond salary, and potential pressures from those in the notoriously high-speed, high-demand world of athletics being chief among them (Chow et al., 2020). That said, many programs have recognized the critical importance of mental health care as well as the need to "keep up" with care that is being provided in other sport organizations and have either already moved or are making plans to move to this model soon.

Counseling centers

Perhaps one of the most convenient means of providing similar services—at least in the collegiate setting—is through the use of the on-campus counseling center. Leveraging the staff and resources of an established facility intended for the general student population can be efficient and cost-effective while at the same time operating free from any potential pressures from athletics department personnel. Many centers include multiple staff members, further facilitating referral or peer consultation for difficult consultation in a way not possible for the common single provider working in athletics (Chew and Thompson, 2014).

Conversely, perhaps the biggest drawback to this model is the lack of consistent preparation among clinicians to work specifically with the athletic population. This can make coordination with other members of the sports medicine team difficult and at times inefficient. Additionally, timeliness of care may not be in line with the typical expectations in the high-pressure athletics environment. Lastly, while this may be a viable option on a large college campus, professional sports teams, small colleges, secondary schools, and other private sport organizations are unlikely to have access to such arrangements.

Outside consultants

Lastly, the final option (other than no provision at all) for providing mental health care services to athletes is through the use of one or more part-time consultants. Like the previous two models, this arrangement has its own inherent strengths and weaknesses. This approach could be as involved as a pre-negotiated baseline of hours provided to the sports medicine team or as informal as an identified professional in the community who will serve as a referral resource on an as-needed basis.

While certainly better than no care at all, this approach can make consistency of care a challenge. For example, some institutions may have arrangements with one sport psychologist for one athletic team and another for others. Services may be limited based on the expertise of the provider and barriers such as transportation to and from the clinic may complicate coordination of care. This model may also seem to perpetuate the notion that mental health concerns are uncommon and not dealt with frequently enough to warrant a more formal arrangement, further perpetuating the stigma associated with seeking care. Particularly for the athlete recovering from significant injury, this model is characteristically inefficient and cumbersome relative to other approaches.

Current theoretical concepts

In order to understand the impact of injury on athletes' psychological well-being, several different theories have been developed, two of which are discussed below.

Integrated sport injury model

The injury process is dynamic, variable, and athlete-specific. Understanding the psychological impact of an injury—how an athlete responds to injury and rehabilitation—is pivotal to a holistic recovery process. Wiese-Bjornstal and colleagues (Wiese-Bjornstal et al., 1998) proposed the Integrated Sports Injury Model (ISI), which is the most accepted and well-developed model to date (Brewer, 2001). It is beyond the scope of this paper to describe the model in full; however, in brief, the ISI encompasses (a) the impact of biopsychosocial variables on the stress response and the likelihood of injury onset, (b) the personal and situational influencing factors, and (c) the cognitive, emotional, and behavioral responses to the injury during the rehabilitation process (**Table 1**).

The foundational component of the ISI is the resulting cognitive appraisals due to the interaction between the precipitating stress response that led to the injury, situation-specific factors, and person-specific factors. Consistent with Beck's cognitive model (Beck and Haigh, 2014), these cognitive appraisals drive the athlete's subsequent emotional and behavioral responses. If the cognitive appraisals are adaptive in nature, the athlete is more likely to head toward full recovery, but if they are maladaptive, then a downward spiral away from full recovery could occur. Ultimately, the ISI demonstrates that the cognitive appraisal process is critical to ensuring successful psychosocial and physical recovery outcomes post-injury.

Sport injury related growth

While a successful injury rehabilitation process is crucial, it is important to consider how we can harness that time to not only help the athlete return to their pre-injury baseline ability but also leverage it as an experience of personal growth to aid in even further wellness and development. In fact, researchers have suggested that after enduring the challenge of a long rehabilitation period, many athletes report being more dedicated, focused, and mentally and physically stronger than they were pre-injury (Wiese-Bjornstal et al., 1998). This is demonstrated in the work by Walker and colleagues (Walker et al., 2007), who expanded on the ISI by increasing insight on the importance of healthy individualized meaning-making throughout the injury experience.

Roy-Davis and colleagues coined the term Sport Injury Related Growth (SIRG) to reflect the multi-faceted development that can be cultivated during recovery form sport injury (Roy-Davis et al., 2017). In brief, SIRG suggests that injured athletes who have certain characteristics (e.g., optimistic explanatory style, access to appropriate resources such as a rehabilitation specialist, previous experiences of adversity to draw upon, emotion- and problem-focused coping styles, and a strong social support system) are more likely to experience positive adaptations and growth post-injury. Specifically, harnessing these characteristics, skills, and resources leads athletes to (a) be more aware of and have control over their thoughts, (b) have greater cognitive reappraisal abilities to view experience as a developmental opportunity, (c) experience positive emotions, and (d) engage in facilitative actions, which in turn lead to positive adaptation and growth in social, mental, physical, and sport-specific domains (Wadey et al., 2020). Recent research has proposed a five-dimension model to describe SIRG in athletes (**Table 2**; Rubio et al., 2020).

TABLE 1 Integrated sport injury model.

Aspect of response	Examples
Pre-injury factors	locus of control, goal orientation, motivation, trait anxiety, history of stressors, coping skills
Personal and situational factors	pain tolerance, athletic identity, injury severity, competition level, social support, mental status
Cognitive, emotional, and behavioral response	self-esteem, rate of perceived recovery, grief, fear of the unknown, rehab adherence, effort

TABLE 2 Dimensions of sports injury related growth (SIRG).

Dimension	Examples
Personal strength	increased empathy, mental toughness, self-reflection, hardiness, optimism, and resilience
Improved social life	improved appreciation for and fostering of relationships and being a member of a team
Health-related benefits	enhanced pain management, awareness of injury prevention, commitment to maintaining health
Sport-related benefits	found a more valuable role on team, worked on technical skills, developed greater mental skills
Social support and recognition	was valued by others beyond the athlete role, received support for needs and responsibilities

Practical applications

Integrated health care

Over the last two decades, Integrated Health Care (IHC) has become a commonly accepted practice to help health care become less fragmented and to shift the focus to treating the whole person from a biopsychosocial standpoint and produce greater patient outcomes in a value-based manner (McDaniel and deGruy, 2014; World Health Organization, 2016). In essence, IHC serves as an overarching term for a dynamic set of principles that seek to provide greater healthcare around the totality of a patient's needs. Within sports medicine, IHC can be seen in the ever-increasing athlete-centered medical homes and the commitment to multidisciplinary physical and mental health (Courson et al., 2014).

This commitment to IHC can be seen in sports injury rehabilitation as well. In addition to the ISI model previously discussed, there have been several other theoretical lines of research that demonstrate the importance of the psychology of injury on a successful rehabilitation process. Personal Investment Theory (Duda et al., 1989) posits that motivation during rehabilitation is determined by personal incentives, sense of self, and perceived options to accomplish recovery and growth. For example, if an athlete sees rehabilitation as a way to get back with the team and satisfy their social needs, believes they are competent and skilled in their sport, and has trust in their rehabilitation specialist(s), they are more likely to be an active participant in their recovery.

Protection Motivation Theory (Floyd et al., 2000) suggests that injury rehabilitation adherence is influenced by the severity and susceptibility of the injury and how effective the patient perceives the intervention(s) to be along with their ability to reliably implement it. In other words, a patient's adherence depends upon factors including self-efficacy, available coping skills, and management of any threat appraisals that arise during the process. Additionally, the Sport Injury Rehabilitation Adherence Model (Brewer, 1998) offers key factors that have the most impact on an athlete's adherence level. For example, (a) behaviors such as compliance and enthusiastic engagement with the rehabilitation plan, (b) personal factors such as intrinsic motivation, cognitive flexibility, and task and mastery goal orientation, and (c) positive beliefs surrounding the rehabilitation process stemming from social support, comfort and convenience of the rehabilitation program and setting, and trust in the rehabilitation specialist(s) all lead to greater adherence throughout the process. Overall, these models continue to demonstrate the importance of the consideration and implementation of psychological skills and interventions within the athletic injury rehabilitation process.

Psychological interventions

While there are an array of effective psychological skills that have been found to aid and facilitate recovery and growth during the injury rehabilitation process, robust evidence is lacking due to inter-athlete variability. However, a limited number of meta-analyses have been published to date regarding general psychological interventions with injured athletes (Ivarsson et al., 2017; Zakrajsek and Blanton, 2017; Gledhill et al., 2018; Gennarelli et al., 2020; Li et al., 2020). In general, these works identified the following interventions to be effective for promoting recovery after a sports injury: imagery, relaxation, goal setting, positive self-talk, coping skills, modeling, psychoeducation, biofeedback, and social support. Likewise, the implementation of these interventions produced positive mood changes, improved self-efficacy, reduced stress and anxiety, improved motivation and satisfaction, healthier cognitive appraisals, more effective pain management, enhanced exercise compliance, and overall improved rehabilitation adherence, suggesting that they are effective and beneficial for injured athletes.

Beyond these individual psychological skills, there are three relatively commonly employed and evidence-based psychological interventions that have not only demonstrated effectiveness in positively impacting the injury rehabilitation process but are used across a wide-array of mental and behavioral health concerns. These include Mindfulness-Based Stress Reduction Training (MBSR), Acceptance and Commitment Training (ACT), and Motivational Enhancement Training (MET). Each is a manualized treatment that can also be adapted in various ways as applied interventions.

Mindfulness-based stress reduction training

First, MBSR focuses on strategies grounded in mindfulness meditation as a self-regulatory approach to stress reduction and cognitive and emotional management (Kabat-Zinn, 2003). MBSR's primary components include education on mindfulness and meditation practices that incorporate various breathing and cognitive techniques. As a standardized protocol, MBSR is an eight-week stress reduction program that starts with a group retreat as an introduction to mindfulness meditation, weekly group sessions focused on meditation practice, group discussion, mindfulness skill-building activities, and daily individual meditation practice. During the injury rehabilitation process, athletes who complete MBSR have demonstrated increased pain tolerance, increased frequency of daily mindful states, and reductions in psychological distress (Mohammed et al., 2018). Beyond MBSR, other mindfulness-based interventions have also been utilized with athletes, such as Mindfulness Sport Performance Enhancement (MSPE) (Kaufman et al., 2018). In general, mindfulness as a foundational component can also be pulled out as an intervention, as mindfulness has been associated with greater self-regulation *via* metacognitive awareness, decreased cognitive rumination and emotional reactivity, increased cognitive flexibility, and greater attentional capacity (Davis and Hayes, 2011; Tang et al., 2015; Guendelman et al., 2017).

Acceptance and commitment training

Acceptance and commitment training (ACT) focuses on strategies aimed at increasing psychological flexibility (Hayes et al., 2012). Much like MBSR, the foundational component of ACT is mindfulness along with the added component of committed action that is grounded in core values rather than goals. More specifically, ACT has six core therapeutic processes: (1) being psychologically present, (2) noticing but not getting caught up in our thoughts, (3) opening up and making room for our feelings, (4) understanding that we are not our actions, feelings, or thoughts, (5) knowing our values, and (6) engaging in intentional behavior that is guided by our actions. While there have been few treatment studies on ACT during sport injury rehabilitation, insights that can be gleaned from the literature, in general, demonstrate the likelihood of effectiveness and its relationship with the central tenants of ISI and SIRG.

Acceptance and commitment training has been considered a unified model of behavior change given that it is transdiagnostic, process-focused, and flexible with broad applicability (Dindo et al., 2017). ACT has been found to lead to improved mood states, decreased anxiety, greater quality of life, and more effective management of fatigue and chronic pain, among others (Hayes et al., 2006). The primary mechanisms within ACT that lead to change and improved outcomes across an array of clinical presentations are increasing psychological flexibility and decreasing experiential avoidance (Stockton et al., 2019).

Motivational enhancement training

Motivational Enhancement Training (MET) focuses on strategies to strengthen personal motivation for and commitment to a specific goal by exploring the person's own reasons for change within an atmosphere of acceptance and compassion (Miller and Rollnick, 2013). The foundational component of MET is motivational interviewing, which is a collaborative, goal-oriented style of communication that pays particular attention to the language of change. It is designed to strengthen personal motivation for and commitment to a specific goal by eliciting and exploring the person's own reasons for change within an atmosphere of acceptance and compassion (Rollnick et al., 2010). The five principles of MET include expressing empathy *via* reflective listening, developing the discrepancy between current and future self, rolling with the resistance and diverting or directing toward positive change, avoiding argumentation, and supporting self-efficacy. The four processes of MET include engaging and building a foundational relationship, defining and focusing the discussion on the target of change, evoking reasons and abilities for change, and building commitment to change and planned action.

Much like ACT, while there have been relatively few treatment studies on MET focused on sport-related settings, early findings suggest that the technique is effective and can help keep the patient sufficiently motivated and engaged in the rehabilitation plan. Generally speaking, MET has been found to lead to improved patient outcomes across a broad range of physical and mental health issues, particularly in part due to stopping or preventing health-interfering behaviors and engaging in health-promoting behaviors (Rollnick et al., 2008). The primary mechanism within MET that leads to more productive behaviors is establishing intrinsic motivation for change to overcome ambivalence (Csillik, 2015). Practically, motivational interviewing is often used as a technique in and of itself that gets combined with other cognitive and behavior therapies, such as ACT.

Creating an integrated health care rehabilitation environment

A commitment to IHC and the biopsychosocial mechanisms that impact the injury rehabilitation process is necessary for SIRG. Healthcare professionals working with athletic populations—particularly with a focus on injury rehabilitation—must find ways establish an integrated rehabilitation environment grounded in the ISI. There are two primary mechanisms to accomplish this task. First, we must expand our conception of sports medicine and ensure the presence of a mental health professional on the multidisciplinary treatment team. Doing so allows for more effective and immediate psychological interventions necessary for recovery and post-injury growth. Second, we must ensure that medical health professionals are adequately trained in relevant psychology of injury theories and related psychological interventions (as appropriate). This can serve as a prevention method to mitigate potential adherence issues, can augment and reaffirm the work of the mental health professional with the athlete, or simply help the medical health professional provide more appropriate care if there is not an ability to have a mental health professional on the treatment team. Additionally, given the role of the environment on the injury rehabilitation process, we must provide education to the entire athletic system and social support network around the injured athlete. Such inclusive education can most assuredly help foster a greater injury rehabilitation process, spur on post-injury growth, and increase the likelihood of peak performance upon return to play.

Future directions

Injury rehabilitation is a crucial component of the sport realm, and advancements in our understanding of not only the physical, but also psychological/mental/emotional aspects of the recovery process continue to evolve. Integration of a comprehensive and qualified sports medicine team can and should be considered as a standard of care to which all athletes are entitled. Furthermore, systematic and rigorous research should be utilized to increase our understanding of the psychological rehabilitation process to better inform how practitioners can provide the most effective and holistic response to an injury event.

Author contributions

TJB served as first author of the work and contributed to the conceptualization, initial drafting, revision, and final formatting of the manuscript. TCB served as second author of the work and contributed to the conceptualization, initial drafting, and revision of the manuscript. JAP served as third author of the work and contributed to the conceptualization, initial drafting, and revision of the manuscript. All authors contributed to the article and approved the submitted version.

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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frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 30 August 2022
DOI 10.3389/fpsyg.2022.905772

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OPEN ACCESS

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

RECEIVED 27 March 2022
ACCEPTED 08 August 2022
PUBLISHED 30 August 2022

CITATION
Wieland B, Fleddermann M-T and Zentgraf K (2022) Acute effects of real and imagined endurance exercise on sustained attention performance.
Front. Psychol. 13:905772.
doi: 10.3389/fpsyg.2022.905772

Acute effects of real and imagined endurance exercise on sustained attention performance

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This study investigated acute effects of real and imagined endurance exercise on sustained attention performance in healthy young adults in order to shed light on the action mechanisms underlying changes in cognitive functioning. The neural similarities between both imagined and physically performed movements reveal that imagery induces transient hypofrontality, whereas real exercise reflects both transient hypofrontality effects and the global release of signaling factors (e.g., BDNF or serotonin) due to muscle contraction and the accompanying sensory feedback. We hypothesized improved cognitive functioning after both interventions (imagery and physical endurance exercise) with greater improvements for real exercise because it targets both mechanisms. Fifty-three sport science students completed two 25-min sessions of moderate endurance exercise in either a motor imagery modality or an executed bodily activity within the framework of an order-balanced crossover study. Assessments for sustained attention performance (d2-R) were performed before and after each endurance exercise condition. Statistical results showed improvements for both groups over time, which can mostly be explained by retest effects. However, we observed a significant interaction effect between group and time, $F(1.6, 81.9)=3.64$, $p=0.04$, $\eta^2=0.07$, with higher increases in the first session in case physical endurance exercise was performed compared to motor imagery exercise, $t(51)=-2.71$, $p=0.09$, $d=0.75$. This might suggest that the release of signaling factors due to muscle contractions with sensory feedback processing is an additional mediating mechanism alongside motor-related transient hypofrontality that improves cognitive performance.

KEYWORDS

hypofrontality, cognition, motor imagery, running, sustained attention

Introduction

Being active in sports might enhance not only physical health and physical performance but also mental health (for overviews, see Biddle and Asare, 2011; Kramer, 2020). Many studies have shown that regular sport exercise can have numerous positive (mental) effects such as reducing the risk of some neurological diseases (Kramer et al., 2006), delaying the onset of age-related decline (Vivar, 2015), positively changing mood (for an overview, see Liao et al., 2015), and also improving some cognitive functions (Labban and Etnier, 2011; Prakash et al., 2015). However, it is not just regular (chronic) sport exercise that enhances mental health or performance. Even a single bout of (acute) sport exercise can also affect some mental aspects. In one of the first reviews, Tomporowski and Ellis (1986) showed that a single session of physical exercise influences cognition (e.g., cognitive tasks measuring working memory or attention). Most of the growing number of empirical studies in this field have shown short-term improvements in cognitive performance after acute exercise in, e.g., single or choice reaction tasks (López-García et al., 2019), different attention tasks (Park and Etnier, 2019), or working memory tasks (Labban and Etnier, 2011). These improvements are found especially in cognitive functions associated with prefrontal regions of the brain (Basso et al., 2015) such as those assessed with attention tasks. Moreover, there are also some reviews (Basso and Suzuki, 2017) and meta-analyses (Etnier et al., 2006; Chang et al., 2012) showing that one single exercise session has a small overall positive effect on cognitive functions. However, although there are many studies showing cognitive improvements after a single bout of exercise, comparisons between these studies and the related neurophysiological and neurochemical changes are constrained by a lack of clear and common standards (Basso and Suzuki, 2017).

There is also a growing literature examining neurochemical changes and neurophysiological changes as a result of acute exercise. Neurochemical components such as neurotrophic factors [e.g., brain-derived neurotrophic factor (BDNF) or insulin-like growth factor 1 (IGF-1)], metabolites (e.g., lactate) as well as neurotransmitters (e.g., serotonin) play an important role in brain plasticity, neuronal development, and cognitive function. Zimmer et al. (2016) studied the effects of acute exercise on serotonin and found increased serotonin levels after moderate aerobic exercise along with improved performance in a Stroop task. In addition, there is also evidence for increased BDNF levels after acute exercise in the form of moderate effect sizes (for an overview, see Szuhany et al., 2015) that correlate with enhanced cognitive performance (Winter et al., 2007).

A complementary approach to explaining cognitive improvements after exercise is based on the reticular-activating hypofrontality theory of exercise (Dietrich, 2006). Findings from a meta-analysis by Jung et al. (2021) corroborate this conceptual idea by presenting data that prefrontal-cortex-dependent cognition *during* exercise is impaired when a limited supply of energy and resources of the brain are shifted away from the prefrontal cortex to more posterior areas for movement execution. Immediately *after* the exercise session and the exercise-induced drain, there is a backward shift of oxygenated blood in the anterior regions of the prefrontal cortex. Due to this backward shift, cognitive performance could be improved. This is an explanation as to why especially cognitive functions involving the prefrontal cortex, such as attention, are often improved after acute exercise (Chang et al., 2012), and why observations with fMRI scans suggest that brain regions important for attention or executive control are affected after an acute bout of exercise (Weng et al., 2017).

It is difficult to clearly separate the mechanisms of signaling pathways (e.g., BDNF, serotonin) from those of cerebral shifting effects (transient hypofrontality) during physical activity because both occur simultaneously during exercise. Therefore, it is also difficult to attribute the amount of the effect to either the hypofrontality hypothesis or the released factors. One approach has been taken by Budnik-Przybylska et al. (2021) who presented evidence for a transient hypofrontality during self-produced motor imagery (MI). MI is characterized as an internal simulation of a movement without corresponding motor output (Jeannerod, 1994), i.e., without muscle contractions. MI has various effects such as promoting motor learning (Di Rienzo et al., 2016) or leading to strength gains (Yue and Cole, 1992). There are several theories addressing the underlying mechanisms of MI. One is simulation theory in which it is assumed that MI is based on the same representations as those that are also used for motor execution. This theory is referred to in studies examining activation patterns between MI and actual movement in cortical areas (Lotze et al., 1999; Jeannerod, 2001; Munzert et al., 2009). For instance, the frontal motor area has been shown to represent content and modality of both imagined and executed actions (Pilgramm et al., 2016). Nonetheless, although these patterns overlap, they are not identical (Zabicki et al., 2017). Considering these similarities between MI and executed actions, it can be hypothesized that the effects of the hypofrontality hypothesis may also be observed when applying MI. Therefore, it seems feasible to use an MI condition to address cerebral shifting effects (transient hypofrontality) and a physical exercise (PE) condition to address the release of signaling factors (e.g., BDNF, serotonin) due to muscle contraction along with the respective sensory feedback, although these mechanisms are not measured in this study directly.

There are also some inconsistencies in the results of previous studies. These can be explained partly by different groups (e.g., children or elderly; physically trained or untrained participants) but also by different study designs using various intervention protocols. On the one hand, physical activity varies in terms of, e.g., the type of activity (such as walking or swimming), its duration (short or long), and its intensity (submaximal or maximal). On the other hand, the cognitive tests used also vary (e.g., memory or attention). For this reason, Basso and Suzuki (2017) suggested clear and common standards for future studies analyzing acute exercise effects on cognition or behavior. They proposed that researchers should consider and report the parameters listed in Table 1. These are: (1) duration, (2) intensity, (3) perceived exertion, and (4) exercise index. A meta-analysis (Chang et al., 2012) identified three further potential moderators: (5) type of cognitive performance and (6) participants' fitness. In addition, effects are influenced by (7)

TABLE 1 Recommended acute exercise study standards and values based on Basso and Suzuki (2017, Points 1–4: Duration, Intensity, Perceived exertion, and Exercise index) and Chang et al. (2012, Points 5–7: Cognitive performance, Participants' fitness, and Timing of testing) and values used in the current study.

Acute exercise measurement and category	Recommended values	Values in current study
(1) Duration (measured in min)		
Short	0–15 min	
Moderate	16–45 min	25 min
Long	46 min or longer	
(2) Intensity (measured in percentage of VO2 max or percentage HR max)	(% VO2 max)	(% HR max)
Low	≤39	
Moderate	40–59	70
High	≥60	
(3) Perceived exertion measured by the Borg Ratings of Perceived Exertion Scale	6–20	6–20
(4) Exercise index a combined value of duration, intensity and perceived exertion	Calculation: (% of hour + % of VO2 max + % of scale)/3	Calculation: (% of hour + % of HR max + % of scale)/3
(5) Cognitive performance	Different cognitive tests	d2-R (sustained attention)
(6) Participants' fitness	e.g., maximal VO2, daily activity	Activity over last 4 weeks
(7) Timing of testing	During	
	Immediately after	
	With a delay	20-min delay

timing of testing (e.g., during exercise, immediately following exercise, or after a delay). Therefore, we added these three further parameters to Table 1.

Based on the above-mentioned literature and the recommendations regarding the study design (Chang et al., 2012; Basso and Suzuki, 2017), the present study aimed to examine the effects of a single bout of PE and of a matched MI endurance session on sustained attention. The idea was to gain further insights into the mechanisms of cognitive functioning after bodily or mental activity. We hypothesized that both interventions—PE and MI—would have positive effects on cognitive performance, with higher increases in sustained attention after PE compared to MI sessions due to the global release of signal factors (such as an increase in BDNF) that can be expected based on the literature. Hence, MI should reflect the improvements due to transient hypofrontality effects, whereas PE should add differential signal factors to the transient hypofrontality effects.

Because previously reported studies chose different designs and did not report all parameters, comparability is difficult. Therefore, by specifying the precise load as well as the test execution parameters in line with the recommendations of Basso and Suzuki (2017) and Chang et al. (2012), this study aims to contribute to a better comparability and interpretation of acute cognitive effects after physical activity. According to the potential moderators (intensity and duration of exercise, as well as cognitive test and timing) for improvement after physical activity identified by Chang et al. (2012) in their comprehensive meta-analysis, the present study is designed to produce potentially high effects.

Materials and methods

Participants

Participants were 56 sport students at the University of Frankfurt, Germany. Their age range was 20–35 years (M = 23.04 years, SD = 3.14) and 29 were male. The study fulfilled the requirements of the local ethics committee, and informed consent was obtained from all participants prior to any data collection.

Procedure

After arriving and being informed about the testing protocol, participants gave written informed consent and filled in a German-language physical activity, exercise, and sport questionnaire (BSA 2.0-Fragebogen from Fuchs et al., 2015) to assess their physical activity over the last 4 weeks. Then, all participants performed the d2-R test in a group setting to measure sustained attention performance. To match the experimental groups for their initial level, participants were pairwise matched according to gender and performance in the pre-test.

Both groups completed two moderate training sessions in a crossover design (see Figure 1). One training session consisted of a moderate PE; the other, of a moderate mental exercise (MI) matched for duration. Moderate exercise was chosen to keep the physiological load between PE and MI more comparable than MI to intense exercise. Both sessions

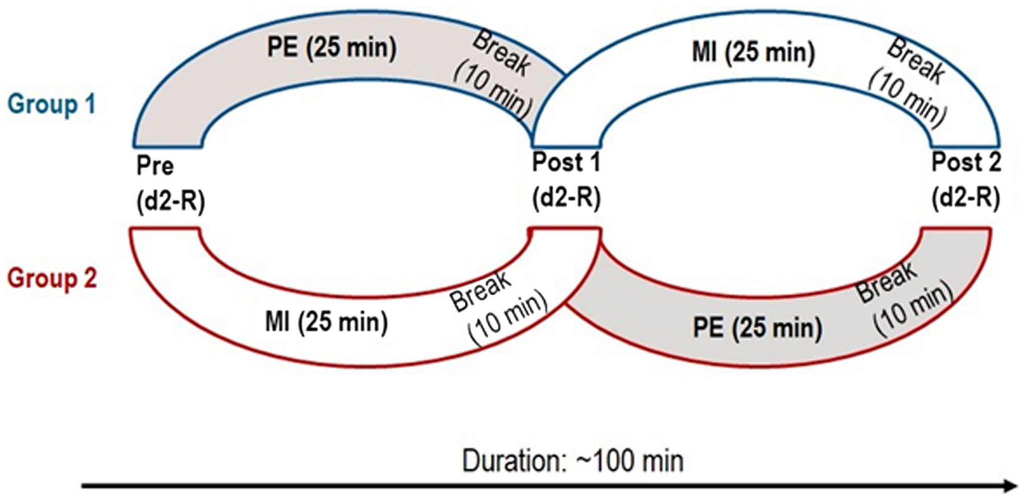

FIGURE 1
Timeline of the experiment. Group 1 first completed the physical exercise (PE) and then the mental imagery exercise (MI). Group 2 first completed MI and then PE. Both groups completed a test for sustained attention (d2-R) three times.

lasted exactly 25 min. Precisely 10 min after each moderate training session (PE or MI), participants performed the d2-R test again (Post 1, Post 2). Participants performed the posttests in the same group setting and sitting in the same seats. The d2-R instructions were repeated in exactly the same way before both posttests.

Physical exercise

The physical endurance exercise was performed on a 400-m track. Each participant's pace was based on their individual heart rate. As recommended by Basso and Suzuki (2017), the individual maximal heart rate (HR_{max}) of each participant was calculated in line with Tanaka et al. (2001) as 208 – (0.7 * age). Heart rate was controlled *via* monitors (Polar F6; Polar Electro, Kempele, Finland). Participants had to adjust their running speed to run at a moderate intensity of 70% of individual HR_{max}. All participants were familiar with pacing their running speed with the help of heart rate monitoring from endurance classes. A research assistant recorded and verified time and running speed after each lap (400 m) according to their individual HR and gave feedback about their pace. They also recorded the total running distance at the end of the session. Total running distance was used as an indicator of physical performance: the longer the running distance, the better the endurance performance. As a manipulation check, we asked students to report their rate of perceived exertion (RPE) on the Borg scale from 6 to 20 (corresponding to a normal heart rate range of 60–200) used to measure overall exertion during physical activity (Borg and Kaijser, 2006). We used the data from the Borg scale, the duration of exercise sessions, and heart rate to calculate an exercise index based on Basso and Suzuki's (2017) equation.

$$\text{Exercise index} = \left(\begin{array}{l} \text{\% of hour for session} \\ + \text{\% of } HR_{max} + \text{\% of scale} \end{array} \right) / 3$$

Motor imagery

The MI session was developed from Holmes and Collins's (2001) PETTLEP model (Physical, Environment, Task, Timing, Learning, Emotion, Perspective). The instructions describe the process of a moderate mental running session from a first-person perspective. Participants were located on the track and each received their medium-intensity instructions *via* a sound recording. During the 25-min MI session, students sitting on the track felt the track under their feet, but were not allowed to move or run. To check their imagery, 5 min after the MI session, participants were asked to describe the amount of time they spent focused on the imagery task (in percent) and to rate the vividness of their overall motor imagery session (Zabicki et al., 2017) on a Likert scale from 1 (*absolutely clear and lively*) to 5 (*absolutely no imagination*) in the format of the VMIQ-2 (Roberts et al., 2008).

Sustained attention test

We measured sustained attention with the d2-R test (Brickenkamp et al., 2010), a paper-and-pencil test in which participants mark special letters under time pressure. In 14 lines with 47 letters, the letters "p" or "d" are presented in a randomized order with one, two, three, or four vertical stripes either above or below each "p" or "d." The instructions are to mark the letter "d" with two stripes, to ignore those with one, three or four stripes, and work as quickly and correctly as possible. Each line has a 20-s time limit, and because there is no break between lines, the total test time is 4 min and 40 s. We administered the d2-R as a group test. The dependent variable was sustained attention performance, which is composed of the marked targets (letter "d" with two strikes) and errors (omitting a "d" with two strikes or marking a false one). The final score is calculated according to an age reference with a maximum score of 130. Participants performed the test in a lecture hall with at least two or more vacant seats to their left and right.

Statistical analyses

Statistical analyses were performed with the software SPSS (IBM SPSS Statistics for Windows Version 25) and alpha was set at 0.05 for all statistical tests. Data were tested for normal distribution and homogeneity of variance using Shapiro–Wilk and Levene tests prior to the statistical analyses. To control for carryover effects, a specifically recommended unpaired *t*-test as suggested by Wellek and Blettner (2012) was calculated. We applied a Greenhouse–Geisser adjustment for violation of sphericity. Two repeated-measures analyses of variance (ANOVAs) were computed to examine the effects of condition (MI, PE) over time (pre, post) and the effects of group (MI-first, PE-first) over time (Pre, Post 1, Post 2). For post hoc comparison, the percentage change score between Pre to Post 1 and Post 1 to Post 2 was calculated for both groups and compared using an independent *t*-test. The effect size of the respective *t*-tests was reported with Cohen's d. Additionally, the effect size of the PE compared to the MI intervention from Pre to Post 1 was calculated using the mean values and standard deviation of Pre and Post 1 and the number of participants of each group with the freeware of Lenhard and Lenhard (2016).

Results

Three participants were excluded from the analyses: two due to wrong test processing of the d2-R, and one due to technical difficulties with the heart-rate monitor. The 53 analyzed persons were divided into Group 1 (that started with PE) with 26 persons ($M = 23.00$ years, SD = 3.73, 14 male) and Group 2 (that started with MI) with 27 persons ($M = 23.10$ years, SD = 2.21, 15 male). Participants reported a mean of 1,523.9 (SD: ±856.5) min of sporting activity during the last 4 weeks and ran an average of 3,392.5 (SD: ±443.3) meters during the 25-min PE session. Based on the World Health Organization (2022) recommendations of 75–150 min of physical activity per week (results in 300–600 min over 4 weeks) for adults aged 18–64 years, the participants in this study are physical active for more than twice the time and therefore can be classified as physical active. RPE for the PE session was rated at a mean of 9.6 (SD: ±1.9) and the average heart rate was 142.9 (SD: ±10.9; target value: 143.9 ± 1.7) bpm. The calculated exercise index was an average of 45.89 (SD: ±4.74). MI sessions were rated as being moderately clear and vivid ($M = 3.2$ points from a maximum of 5 points, SD: ±0.9), and participants reported that they focused $M = 55.1\%$ (SD: ±22.2) of the time on imagery.

Comparison between conditions

Test for carryover effects showed no significant differences, $t(51) = -1.29$, $p = 0.20$, $d = 0.35$, which is relevant for crossover designs to yield valid results. The 2 × 2 (Condition × Time) ANOVA showed no interaction effect, $F(1, 52) = 0.05$, $p = 0.82$, $\eta^2 = 0.001$, and no significant main effect for condition, $F(1, 52) = 0.05$, $p = 0.82$, $\eta^2 = 0.001$, but a significant main effect of time, $F(1, 52) = 265.89$, $p < 0.001$, $\eta^2 = 0.84$ (see Figure 2).

Comparison between groups

Mauchly's sphericity test indicated that the assumption of sphericity had been violated for the score in d2-R over time (Pre, Post 1, Post 2), $\chi^2(2) = 14.01$, $p = 0.001$. The 2 × 3 (Group × Time) ANOVA with a Greenhouse–Geisser correction revealed a significant interaction, $F(1.6, 81.9) = 3.64$, $p = 0.04$, $\eta^2 = 0.07$ and a significant main effect time, $F(1.6, 81.9) = 197.03$, $p < 0.01$, $\eta^2 = 0.79$, but no main effect group, $F(1, 51) = 0.97$, $p = 0.33$, $\eta^2 = 0.02$. Prescores of both groups were not different ($t(51) = -0.23$, $p = 0.82$, $d = 0.07$), but improvement from Pre to Post 1 was higher for the PE-first group (9.1%) than for the MI-first group (6.4%; $t(51) = -2.71$, $p = 0.09$, $d = 0.75$). Further increases from Post 1 to Post 2 did not differ between both groups ($t(51) = 0.19$, $p = 0.85$, $d = 0.05$): 2.9% (PE-first) and 2.6% (MI-first, see Figure 3).

Discussion

The present study examined the effects of a single session of physical endurance exercise (PE) as well as the effects of a single session of an imagined endurance exercise (MI) on a sustained attention task with the aim of gaining further insights into the mechanisms underlying exercise-induced cognitive improvements. In this context, the MI condition reflects improvements based on cerebral shifting effects, whereas the PE condition reflects improvements based on various mechanisms that include cerebral shifting, but in addition others such as global or local release of signaling factors that act on pathways for functional and structural cerebral changes.

We hypothesized improvements in both conditions, but greater improvements after the PE intervention because this involved both mechanisms. At first glance, the primary finding of the study is an enhanced cognitive performance in the d2-R for both conditions (PE & MI), but due to the known retest effects in cognitive tests (d2-R; Schmidt-Atzert et al., 2021), results must be examined in more detail. Because we investigated retest effects with two instead of three measurement points, results were analyzed within groups (i.e., in the order Pre, Post 1, and Post 2 with the different starting conditions

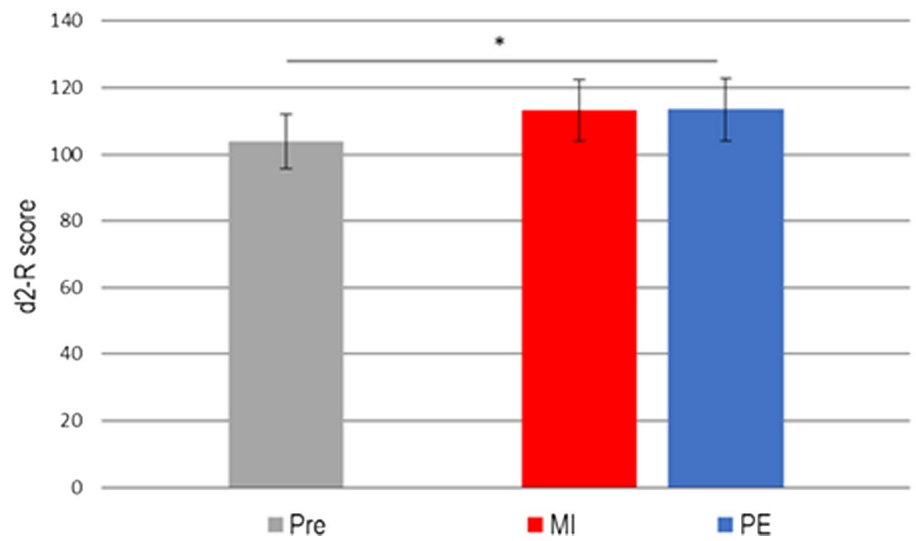

FIGURE 2
Mean (±SD) d2-R score before (Pre) and after MI or PE exercise. Significant difference (*$p < 0.05$) between pre and both post MI and post PE.

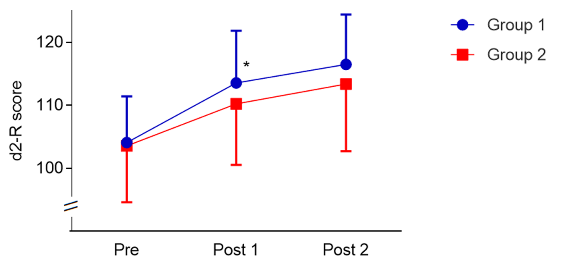

FIGURE 3
Change in d2-R score (Mean±SD) of both groups (Group 1, PE First; Group 2, MI first) over time. Significant interaction (*$p < 0.05$) between time and group with higher score for Group 1 at Post 1.

PE-first vs. MI-first) instead of using averaged MI and PE values for both measurement times. In addition to the main effect of time, this analysis reveals an interaction effect between time and group. Prescores of both groups did not differ, but improvement from Pre to Post 1 is higher (9.1%) in the PE-first group than in the MI-first group (6.4%). Further increases from Post 1 to Post 2 are lower and similar in size for both groups: 2.9% (PE-first) and 2.6% (MI-first). Comparing improvements in the MI-first group after the first intervention (i.e., after MI) with values addressing retest effects under comparable conditions (similar baseline score and time between both test executions; see Brickenkamp et al., 2010) reveals a percentage improvement of 5.9%. This comparison suggests that the MI intervention does not show any additional effect going beyond the retest effects, and that only those with PE in the first session benefit cognitively from their activity. After the second session, both groups show a low improvement from Post 1 to Post 2 (2.9% and 2.6%), but the groups do not differ. We hypothesize that the absence of an effect due to PE could be explained by a ceiling effect of repeated testing. Which means, according to the compensation theory (Karbach and Unger, 2014) that individuals benefit fewer from cognitive training if the room for improvement is less. As participant's starts with a higher score into the second intervention phase, the level for improvement is less for both groups, which could be why PE cannot achieve the expected results for the MI first group during the second intervention phase. Unfortunately, we cannot draw on results from other studies investigating d2-R to confirm this hypothesis. Another explanation for missing effects that cannot be excluded are cognitive fatigue effects. However, due to the short test duration of the d2-R (4:40 min and in total 14 min), we rather assume low fatigue effects. Furthermore, a carryover effect of the physical activity on the second mental activity cannot be completely excluded. Although the statistical evaluation as well as the expected rapid decrease in heart rate (Pierpont et al., 2000) and heart rate variability (Scott et al., 2017) after moderate physical activity speaks against a washout phase that is too short, signaling factors or other mechanism may still be slightly active. This resulted in the lack of a second improvement after PE, which meant that the analysis of the conditions (PE and MI) did not reveal any significant differences. Therefore, we assume that only PE has a positive effect on sustained attention, and that MI does not. This would suggest that cognitive improvement is more likely to be enhanced by PE, which have been hypothesized to induce a variety of neurobiological mechanisms and not, or at least not only, by a redistribution of neuronal activity in the brain. Possible mechanisms or signaling pathways after PE could be a global release of signaling factors (e.g., neurotransmitter or growth factors), a mediation of brain mechanism, like the orexin system (Chieffi et al., 2017) or an increased blood flow to the brain, which increases the oxygen uptake (Ogoh and Ainslie, 2009).

However, we still need to mention aspects that could explain the absence of effects due to MI, which should induce transient hypofrontality effects. For example, the intensity could have been slightly too low. Indeed, participants show higher performance on prefrontal-cortex-dependent tasks after high-intensity rather than medium-or low-intensity exercise (Crawford and Loprinzi, 2019; Loprinzi et al., 2019). Furthermore, the delay between exercise and cognitive test in our study may be too long (10 min between ending the activity and starting the test) for transient hypofrontality effects, because most studies addressing transient hypofrontality theory tested during exercise or with only a short delay (for a review, see, e.g., Jung et al., 2021). Another aspect is that high physical fitness is a potential moderator for prefrontal-cortex-dependent tasks, and that effects will be lower for highly trained participants (Jung et al., 2021). This could impact on our group of physically rather active participants. However, there is also evidence that participants' individual fitness status is related to an increase in BDNF level after exercise, meaning there is a greater increase in BDNF in trained compared to untrained subjects (Tsai et al., 2016). A higher BDNF level after acute exercise is related, in turn, to better cognitive performance (Winter et al., 2007). This suggests an advantage for the PE condition, since our group includes physically active people. In this context, BDNF represents the signaling factor leading to enhanced cognitive performance after acute physical activity. As mentioned in the introduction, there are other potential factors such as serotonin or IGF-1, but their differentiation was not the goal of our study. We aimed to compare possible cerebral shifting effects against the overall effects after moderate physical activity. Taking into account the above-mentioned constraints, our results indicate that the global release of neurotransmitter or growth factors is necessary for cognitive improvements with a delay after physical exercise.

The effects of physical exercise on sustained attention can be shown in the results from Pre to Post 1. The effect size of PE (MI as control group, calculated with absolute values) from Pre to Post 1 is $d=0.34$ indicating a small positive effect of physical exercise on sustained attention (Lenhard and Lenhard, 2016). This is in line with the outcomes of meta-analyses that also report a small positive effect in studies measuring cognition after exercise (Lambourne and Tomporowski, 2010; Chang et al., 2012). Looking at effect sizes more closely, it can be seen that our study reveals a slightly larger effect than that in Chang et al.'s (2012) and Lambourne and Tomporowski's (2010) meta-analysis ($g=0.10$, $d=0.20$). This might be due to the design of the study and the aforementioned potential moderators, which were based on the results of Chang et al.'s (2012) meta-analysis and Basso and Suzuki's (2017) recommendations (see Table 1), leading to the detection of larger effects. Chang et al. (2012) reported that the duration, the intensity of the load, and the timing of the test influence effects. They stated that at least 20 min of exercise are necessary to see these effects, but that protocols lasting much longer than 20 min are subject to side effects such as fatigue or dehydration. This is why we chose 25 min for our intervention time. Another important issue seems to be the timing of test administration for cognitive function, with largest effects found with a delay of about 11–20 min and a flattening of the effects after 20 min. For intensity, there is some evidence that higher intensities lead to greater effects with a delay after exercise. For lower intensities, the effect is measurable for only a very short time or immediately after the end of the activity. Because we chose a medium intensity in order to ensure every participant would be able to complete the 25 min of endurance activity and keep the physiological load of PE better comparable to MI than with intense exercise, we decided to use a delay time of 10 min. In contrast to Basso and Suzuki (2017), we did not control the intensity *via* percentage of $VO2_{max}$, but *via* percentage of HR_{max} to make our study easier to implement. This is also a valid method for submaximal intensity (Ainsworth et al., 2015). We report perceived exertion as recommended: Values on the Borg scale show that perceived exertion is very light to light. Considering the selected intensity of 70% of HR_{max}, however, we would have expected higher values. The low values may be explained by our participants' relatively high level of fitness. A high fitness level, in turn, acts as a moderator for higher effects on cognitive functions after an acute bout of exercise (Chang et al., 2012). Therefore, we can expect a higher effect in our trained participants. In Chang et al.'s (2012) meta-analysis, greater improvements were measured in attention tests, which is why we chose a test for sustained attention in the current study. To improve comparability between intervention studies examining acute effects on cognitive functions after a single bout of exercise, we calculated and reported an exercise index. The clear presentation and consideration of the load parameters and possible moderators can be used for further analyses or follow-up studies, and results in a comparatively high effect. As more studies report the exact parameters of the intervention and calculate the exercise index according to Basso and Suzuki (2017), the linkage between load and effect can be drawn better.

Finding a good linkage between load parameters and cognitive improvements on acute measurements may also provide conclusions for long-term improvements, as these may result from accumulated acute effects. Indeed, two studies looking for long-term improvements in sustained attention with the same cognitive test as in this study showed higher effect sizes with $d=0.70$ (Stroth et al., 2009) and $d=0.71$ (Lehmann et al., 2020) compared to the shown acute effects in this study.

Overall, we conclude that MI, which is supposed to be associated with the transient hypofrontality hypothesis, has no effect on sustained attention when tested with a 10 min delay. PE, which is supposed to be associated with several mechanisms such as cerebral shifting or the global release of signaling factors, etc., leads to an increase in sustained attention—at least after one test, but not on repeated tests. The calculated effect size is in line with the literature. In order to prevent ceiling effects, future studies should choose a test with lower retest effects or not use a crossover design. By describing the load and cognitive test parameters in detail and implementing two different interventions, this study is relevant for future studies or meta-analyses aiming to gain further evidence on the mechanistic effects of acute exercise on cognition.

Conclusion

The aim of the study was to examine cognitive functioning after a physical and a mental endurance exercise session. Results show improvements for both groups over time, whereby the improvements in the mental group are due to retest effects. However, a greater increase in cognitive functioning after physical endurance exercise emerges when it is operationalized as the first session, suggesting that release of signaling factors such as neurotransmitter or growth factors due to muscle contraction and real sensory feedback processing are further mediating mechanisms going beyond transient hypofrontality that improve cognitive performance.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by Goethe University Frankfurt am Main, Department of Psychology and Sports Science, Ethics committee. The patients/participants provided their written informed consent to participate in this study.

Author contributions

BW, M-TF, and KZ designed the experiment, analyzed and interpreted the data, and prepared the manuscript. BW and M-TF performed the experiment. KZ additionally edited the manuscript with the help of a native speaker. All authors contributed to the article and approved the submitted version.

Acknowledgments

We thank Christian Kupper and Manuel Odey for support in data collection.

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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frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 23 September 2022
DOI 10.3389/fpsyg.2022.905816

OPEN ACCESS

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

RECEIVED 27 March 2022
ACCEPTED 22 July 2022
PUBLISHED 23 September 2022

CITATION
Gomez-Espejo V, Olmedilla A, Abenza-Cano L, Garcia-Mas A and Ortega E (2022) Psychological readiness to return to sports practice and risk of recurrence: Case studies. *Front. Psychol.* 13:905816.
doi: 10.3389/fpsyg.2022.905816

Psychological readiness to return to sports practice and risk of recurrence: Case studies

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Returning to sport after the sports injury is a difficult decision because it's multicausal and the fact that a rash decision can result in numerous negative consequences. Given the importance of psychological variables for the correct rehabilitation of the injured athlete and his or her optimal return to sports practice, there seems to be little information on this subject. In this sense, the objective is to determine the relationship between the subjective psychological disposition of the athlete in the process of Return to Play (RTP) with the type of mood profile and his mental health. This is based on the fact that each athlete evaluates his or her recovery differently and has different levels of anxiety, depression, and stress. For this purpose, four athletes participated in the study. Two males and two females from the sports of indoor soccer and soccer, who had just returned to sports after a moderate or severe injury. The average age was 24.25 years. Various measurements were taken after practices and after matches, to assess mood, psychological readiness, anxiety, stress, and depression. The results confirm Morgan's iceberg profile and the influence that subjective psychological perceptions and assessed emotional states have on athletes' incorporation into their sports practice with a guarantee of success.

KEYWORDS

psychological readiness, iceberg profile, RTP, sport injury, recurrence

Introduction

Sports injuries have a negative emotional impact on the health and performance of the affected athlete and result in high health and sports economic cost (Palmi, 2014; Emery and Pasanen, 2019; O'Brien et al., 2019; Kvist and Silbernagel, 2022). After a sports injury, the athlete undergoes a physical rehabilitation process (Baez et al., 2020;

Goddard et al., 2020; Kvist and Silbernagel, 2022). Thanks to technological and medical advances, 90% of athletes undergo rehabilitation regain normal function of the injured area; but only 63% of them return to pre-injury levels and 44% return to competition (Ardern et al., 2011). These results suggest that factors other than the physical play a role in a successful return to sport. In this sense, after the rehabilitation process is completed, the decision is made whether the injured athlete can return to sport (Conti et al., 2019; Green et al., 2020).

For years, researchers have pointed out the importance of psychological factors in sports injury susceptibility (García-Mas et al., 2014; Ganz, 2018; Slimani et al., 2018) and their recovery (Casáis, 2008; Arvinen-Barrow and Clement, 2016; Salim et al., 2016; Roy-Davis et al., 2017; Olmedilla et al., 2018a; Gennarelli et al., 2020). Several theoretical models suggest that personality, coping resources and emotional state influence sports injuries (Andersen and Williams, 1988; Olmedilla and García-Mas, 2009; Johnson and Ivarsson, 2011; Assa et al., 2018; Meierbachtol et al., 2018; Arroyo del Bosque et al., 2020).

There are numerous references that establish relationships between sports injury and the athlete's psychological predisposition to resume sports practice (Chomiak et al., 2000; Forsdyke et al., 2017; Zarzycki et al., 2018; Kunnen et al., 2019; Cheney et al., 2020). For this reason, based on the emotional pattern "U" experienced during the injury process, which maintains the occurrence of negative responses both at the beginning and at the end of the process (Morrey et al., 1999; Ardern et al., 2017), numerous authors have emphasized the importance of a good psychological predisposition before Return to Play (RTP) (Christino et al., 2016; Burland et al., 2018; Caron et al., 2018; Kitaguchi et al., 2019; Ashton et al., 2020). In this sense, lack of psychological preparation has been identified as a factor preventing proper RTP (Risberg et al., 2007; Ardern et al., 2014; Nwachukwu et al., 2019) and may persist even when physical disabilities have been resolved (Ross, 2010; Lentz et al., 2015; Gennarelli et al., 2020).

The Sports Medicine Council (2002) defines Return to Play as the point at which the injured athlete makes the decision to safely return to training and competition (Herring, 2002). Some authors (Hammond et al., 2013; Haitz et al., 2014; Burland et al., 2018; Rollo et al., 2021), caution that the RTP can sometimes be "unreal" as external variables such as environmental pressures coach request, fan demand or the injured athlete's urge to not lose status can lead to a hasty decision. For this reason, any sports injury should be considered from the global framework of the athlete.

The emotional states experienced by the injured athlete during this period of recovery from the sports injury will help determine RTP in one way or another. Specifically, some studies suggest that stress can lead to increased risk of injury and influence their recovery (Nippert and Smith, 2008; De la Vega et al., 2013; Heidari et al., 2016; Olmedilla and García-Mas et al., 2017; Olmedilla et al., 2018b; Leguizamo et al., 2021). Similarly, depression and "low" mood have received particular attention (Purcell et al., 2019). However, knowledge about the relationship between psychological factors and sports injuries is still limited (Olmedilla et al., 2018b; Gouttebarge et al., 2019; Rice et al., 2019). Therefore, it's likely that injured athletes with positive emotional responses achieve better rehabilitation, which would positively correlate with a correct RTP (Sabato et al., 2016; Gomez-Espejo et al., 2018; Nwachukwu et al., 2019; Rollo et al., 2021). Therefore, athletes who are ready for the RTP are more likely to have better emotional responses. Therefore, any apprehension the athlete feels while preparing for the RTP may indicate that rehabilitation is incomplete (Cheney et al., 2020). Conversely, athletes who are not psychologically prepared for the RTP are less likely to return to sport. And those who do return to sport may be at increased risk for recurrence, poor athletic performance and lower-quality of the sport experience (Ardern et al., 2013, 2014; Czuppon et al., 2014; Podlog et al., 2015; Baugh et al., 2017; Brewer, 2017; Green et al., 2020). Therefore, the fact of suffering a sports injury is particularly relevant as it not only represents a physical problem, but also implies a change in the psychological disposition of the athlete. For this reason, Morgan developed his own Mental Health Model (Morgan, 1980), according to which successful athletes have more positive and less negative mental health characteristics than less successful athletes and the general population. The iceberg profile would essentially be the profile of a mentally healthy person (Andrade et al., 2016, 2019; Terry and Parsons-Smith, 2021).

Thus, when returning to sport, athletes express concerns about the prospect of recurrence (Ardern et al., 2013; Flanigan et al., 2013; Czuppon et al., 2014; Brewer, 2017; Meierbachtol et al., 2018; McPherson et al., 2019), have decreased performance or execution ability (Podlog et al., 2013), have deficits in intrinsic motivation to return to their sport (Brewer, 2010, 2017; Ardern et al., 2013; Czuppon et al., 2014; Hamrin-Senorski et al., 2017; Slagers et al., 2017), and they appear physically unable to return to sport (Ardern et al., 2013; Podlog et al., 2013; Czuppon et al., 2014; Brewer, 2017; Hamrin-Senorski et al., 2017; Slagers et al., 2017).

In this sense, RTP and the potential risk of recurrence are often as emotional events as the injury itself and are identified as potential limiting factors for rehabilitation and successful RTP (Creighton et al., 2010; Milewski et al., 2016; Cheney et al., 2020). Although psychological interventions improve sports injury function, it is unknown how psychological preparation influences the risk of a second injury (Lentz et al., 2018). Several studies (Paterno et al., 2012; Webster et al., 2014; Wiggins et al., 2016; Zhang et al., 2022) have shown that many athletes who return to their previous activity level sustain a second injury, demonstrating the importance of psychological health (McPherson et al., 2019). Therefore, it's necessary to develop specific strategies to facilitate decision making about

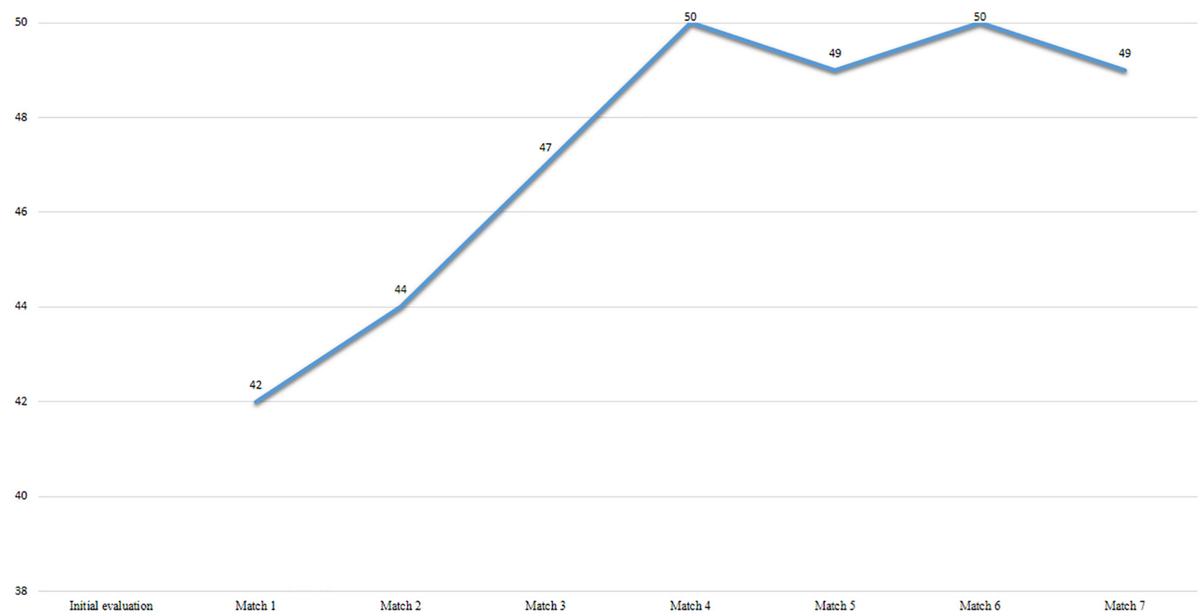

FIGURE 1
Subject 1 PRIA scores.

the ideal time for an injured player to the return to sport (Gómez-Piqueras et al., 2013; O'Brien et al., 2017; Tjong et al., 2017; Webster et al., 2017; Gómez-Espejo et al., 2018; McCrory et al., 2018; McPherson et al., 2019), understanding this as an ongoing decision-making process that needs to be dynamic and personalized (Ekstrand and Gillquist, 1983; Pruna, 2016; Cheney et al., 2020). Although there is currently consensus on the need to examine the physical and psychological factors surrounding RTP (Feller and Webster, 2013; Ivarsson et al., 2013; Takeshita et al., 2016; Forsdyke et al., 2017; Webster et al., 2017, 2018; Lai et al., 2018; Welling et al., 2018; Werner et al., 2018; Baez et al., 2019; Kaplan and Witvrouw, 2019), existing criteria do not comprehensively consider psychological preparation for competition.

For this reason, it is necessary to include strategies for the correct follow-up of the injured that allow to objectify the decisions of the professionals (Gómez-Piqueras et al., 2014, 2020), since, according to Glazer (2009) and Webster et al. (2008), it has been noted that today there are not enough instruments that evaluate in a specific way the psychological predisposition of the injured in the moment before the reappearance, and that include specific questions about this phase and the specifics of the injury. In this sense, Gómez-Piqueras et al. (2014) developed an instrument that measures the perception of the injured athlete in relation to his return to training after an injury, which proved to be effective for this purpose.

The aim of this study is to determine the relationship between pre-RTP subjective psychological disposition and mental health indicators in four cases of injured soccer and futsal players before a pandemic and lockdown situation.

TABLE 1 Values in the POMS factors of Subject 1 after the matches.

Time of evaluation	Tension	Anger	Vigor	Fatigue	Depression
Match 1	4.2	21.8	100	10	0
Match 2	4.2	12.5	60	5	5
Match 3	20.8	0	80	5	0
Match 4	12.5	12.5	95	5	0
Match 5	0	12.5	100	0	0
Match 6	16.7	12.5	100	0	0
Match 7	0	12.5	80	0	0

Materials and methods

Participants

The following inclusion criteria were established for participation in the study: Athletes had to have been discharged by a physician less than one week ago, have sustained a severe or moderate sports injury, not have a chronic physical or mental illness.

Considering all the inclusion criteria and the athlete population that meets them, the work was carried out with 4 soccer players (2 soccers and 2 futsal players) from different sports categories belonging to sports clubs. The average age

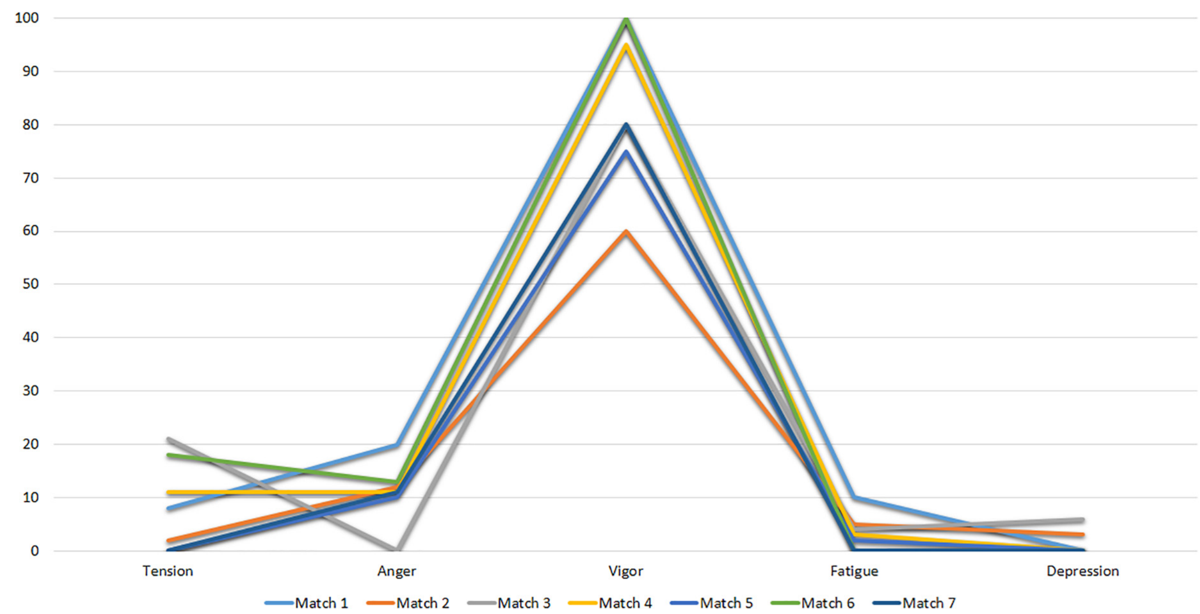

FIGURE 2
POMS profiles of subject I after matchs.

of the athletes was 24.25 years, with an age range between 18 and 28 years. The average number of years they practiced their sport in the highest category was 2.5 years, while the average number of years they practiced the sport continuously was 11 years.

In terms to to the type of sports injury sustained, the inclusion criteria for the study were: that it was a recently rehabilitated sports injury (return to sport two days prior to the initial evaluation), that it was new (no recurrences or relapses) and that it was medically diagnosed as moderate or severe. That is, they were a sports injury with an estimated recovery time of at least 15 days of treatment. The characteristics of the remaining participating subjects to be included in the study are listed below:

Subject 1: 18-year-old male, professional soccer player. He plays as a goalkeeper. He trains 3 days a week, averaging 5 h a week. He suffered a knee sprain that forced him to miss 17 training sessions and 6 games in a row.

Subject 2: 26-year-old female, professional soccer player. She plays as a striker. She trains 3 days per week with an average of 6 h per week. She suffered a dislocated shoulder that forced her to miss 15 training sessions and 5 games in a row.

Subject 3: 25-year-old male, futsal player. He plays in the position of goalkeeper. He trains 3 days per week, averaging 6 h per week. He suffered from shoulder tendinitis, which forced him to miss 12 training sessions and 3 games in a row.

Subject 4: 28-year-old female, futsal player. She plays as a wing player. He trains 4 days per week, averaging 8 h per week. He suffered a torn meniscus, which forced him to miss 22 training sessions and 6 games in a row.

TABLE 2 Values in the POMS factors of Subjetc 1 after training.

Time of evaluation	Tension	Anger	Vigor	Fatigue	Depression
Training week 1	4.2	15.6	90	10	0
Training week 2	4.2	12.5	60	5	5
Training week 3	25	0	90	5	0
Training week 4	12.5	12.5	95	5	0
Training week 5	4.2	15.6	100	0	0
Training week 6	12.5	9.4	100	0	0
Semana entreno 7	0	12.5	80	0	0

Instruments and materials

The psychological assessment instruments used for the study were:

Personal and sports variables questionnaire. Ad hoc questionnaire to collect the athlete's socio-demographic data (see Annex I).

History of sports injuries. Ad hoc created questionnaire, based on an injury protocol (Olmedilla and García-Mas et al., 2017). It captures the number of sports injuries sustained in the last two seasons and specific data about them (see Annex II).

Profile of Mood States (POMS, McNair et al., 1971). In its Spanish version adapted and validated by Fuentes et al. (1995). It is a self-report questionnaire for measuring mood. The short version was used, with 29 items answered on a Likert-type scale with 5 response options. It includes 5 dimensions: Tension

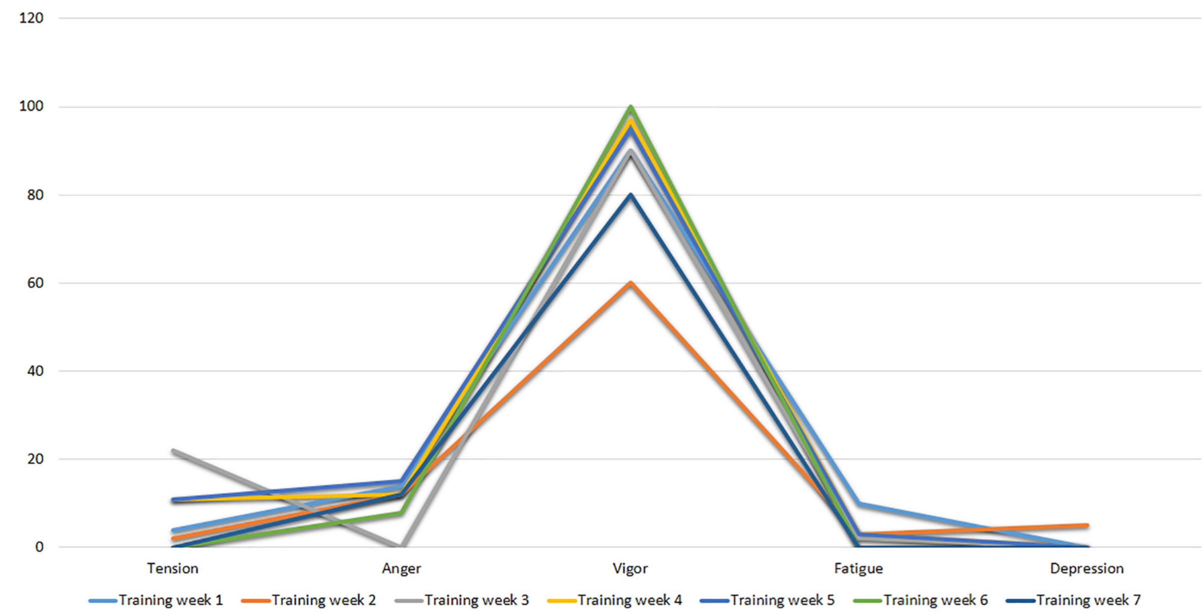

FIGURE 3
POMS profiles of subject I after training weeks.

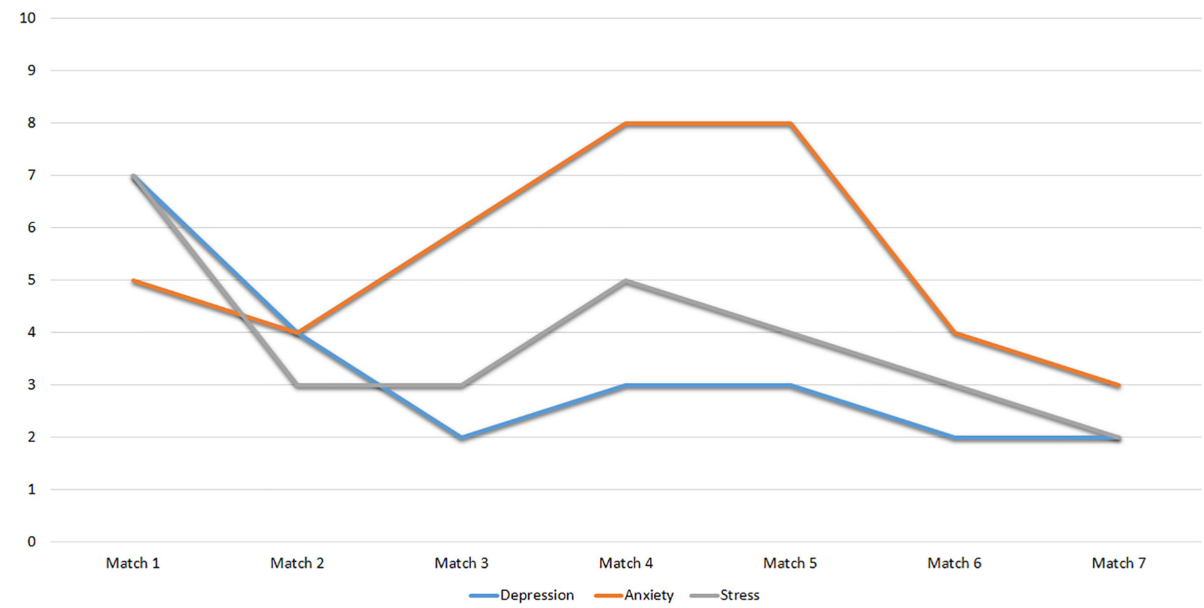

FIGURE 4
Scores of subject 1 to the subscales of the DASS-21.

(α = 0.83); Depression (α = 0.78); Anger (α = 0.85); Vigor (α = 0.83); Fatigue (α = 0.82).

Depression, Anxiety and Stress Scale-21items (DASS-21, Lovibond and Lovibond, 1995). In its version adapted and validated in Spanish (Fonseca-Pedrero et al., 2010). Has been used to measure general symptoms of depression, anxiety and stress. This scale has three subscales: depression, anxiety and stress, each consisting of 7 items, for a total of 21. In a Likert-type response scale, each item has four response options. It has a Cronbach's Alpha of 0.81.

Psychological Readiness of Injured Athlete to return to sport (PRIA, Gómez-Piqueras et al., 2014). The assessment instrument consists of 10 questions/items that include statements about self- confidence, individual

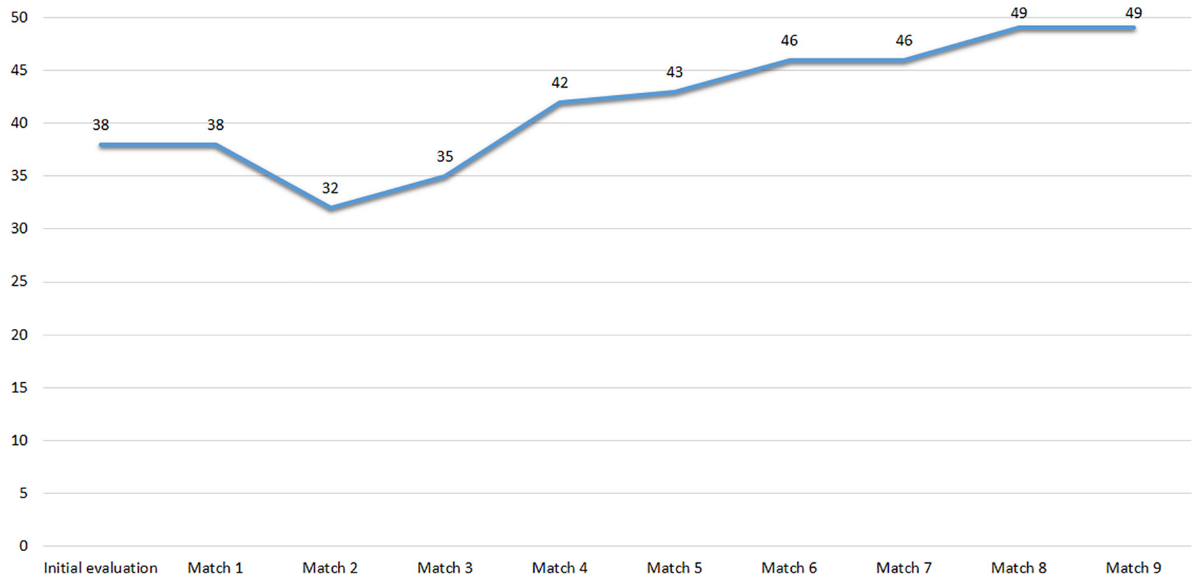

FIGURE 5
Subject 2 PRIA scores.

TABLE 3 Values in the POMS factors of Subject 2 after the matches.

Time of evaluation	Tension	Anger	Vigor	Fatigue	Depression
Match 1	58.3	18.7	75	5	0
Match 2	25	12.5	75	0	0
Match 3	25	9.4	75	0	0
Match 4	25	15.6	75	0	0
Match 5	16.7	15.6	75	0	0
Match 6	4.2	9.4	85	0	0
Match 7	20.8	9.4	75	5	0
Match 8	4.2	12.5	70	0	0
Match 9	16.7	12.5	60	0	0

status, uncertainty and fear of relapse. Scores range from 1 to 5, with higher scores corresponding to better psychological disposition.

Procedure

Prior to the psychological assessment, the rehabilitation staff Football Federation of the Region of Murcia (FFRM) was contacted directly, thanks to a collaboration agreement in place at the time between the University of Murcia (UMU) (an organization in which the psychologist in charge of the study worked) and the FFRM. The rehabilitators served as a link between the psychologist and the athletes, providing the contact details of those athletes who met the inclusion criteria. The purpose of the study and the procedure were explained to the rehabilitators and later to the participating injured athletes (via telephone). In addition, all participants were informed of the purpose of the study and the confidentiality of both their responses and previously collected data. Informed consent and the privacy document were obtained from all participants. The entire evaluation process and subsequent contact was conducted online.

The study was approved under research ethics by the Ethics Committee of the University of Murcia (Spain), with reference number CEI-2623-2019.The moment the athletes were medically discharged from the FFRM, the psychological evaluation by the psychologist in charge of the project began. The evaluation was done online and consisted of three different moments related to the return to play (RTP), so the psychological evaluation process was as follows:

Initial assessment. It's conducted immediately after medical discharge. At this time, an assessment battery consisting of personal and sports variables, PRIA questionnaire and POMS questionnaire was used. For this purpose, an assessment battery was sent online via email, which could be completed directly by clicking on the link.

Monitoring of training. Completed once a week after practices. Recording the date and time of training, as well as the POMS.

Tracking of games. Completed after each match in which the athlete was used. Recorded the POMS, the DASS-21 and the PRIA.

It should be noted that the evaluation process was interrupted earlier than planned when competitions and training were interrupted due to the state of alert and lockdown

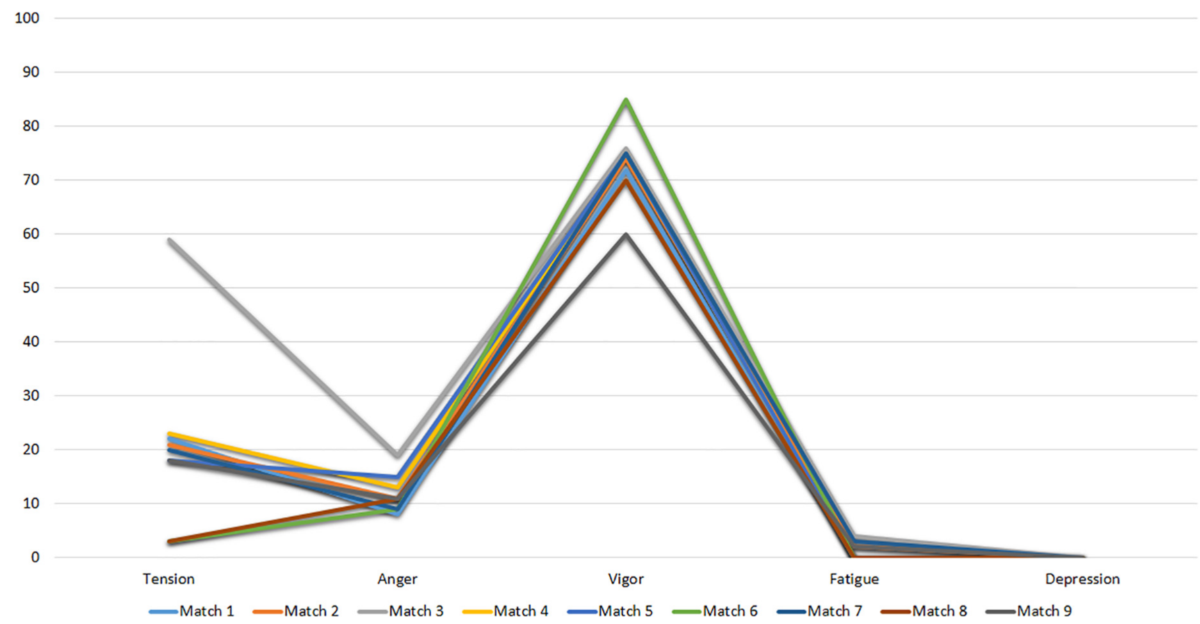

FIGURE 6
POMS profile of subject 2 after matchs.

TABLE 4 Values in the POMS factors of Subjetc 2 after training.

Time of evaluation	Tension	Anger	Vigor	Fatigue	Depression
Training week 1	20.8	12.5	75	5	0
Training week 2	16.7	12.5	75	0	0
Training week 3	20.8	9.4	85	0	0
Training week 4	25	15.6	75	0	0
Training week 5	16.7	12.5	80	0	0
Training week 6	4.2	9.4	90	0	0
Training week 7	20.8	9.4	75	5	0
Training week 8	4.2	12.5	70	0	0

declared by the Spanish Government because of the Covid-19 pandemic.

Data analysis

Descriptive statistics were used for data analysis, employing counts, sums, percentages and measurements. The results of the POMS questionnaire were converted to a scale of 0 to 100 points, with 50 being the mean. Participants' pre-competition mood profile were analyzed and described. The graphs of the pre-competition and pre-training mood profiles were created. Likewise, the graphs were made with the results of the PRIA questionnaire. The statistical program SPSS 22.0 was used.

Results

Subject 1 results

Figure 1 shows the scores obtained in the Questionnaire of psychological predisposition of the injured athlete (PRIA) during the evaluation. Scores above 40 indicate that the athlete's psychological disposition is sufficient to return to play with some degree of confidence. The lowest value of 42 points means that the athlete is psychologically ready to return to play. Moreover, it can be observed that the psychological predisposition increases progressively until the third game and then stabilizes.

Table 1 shows the values that Subject 1 obtained on the POMS factors in the seven shots evaluated after the matches.

Figure 2 shows the mood profiles of Subject 1 at the evaluation time points after the competition (Match 1 to Match 7).

The results of these figures correspond to the iceberg profile described by Morgan (1980), which shows no change in mood states before the competition. In this sense, the profile obtained by Subject 1 is characterized by low scores in Tension, Anger, Fatigue and Depression and a level in the Vigor factor above the central value (50).

Table 2 shows the values obtained by Subject 1 in the POMS factors in the seven shots evaluated weekly after training.

Figure 3 shows the profiles of Subject 1 in the first three assessment time points after training (Training Week 1 to Training Week 7). As can be seen, Subject 1 shows an ideal pre-competition mood profile, consistent with the iceberg profile,

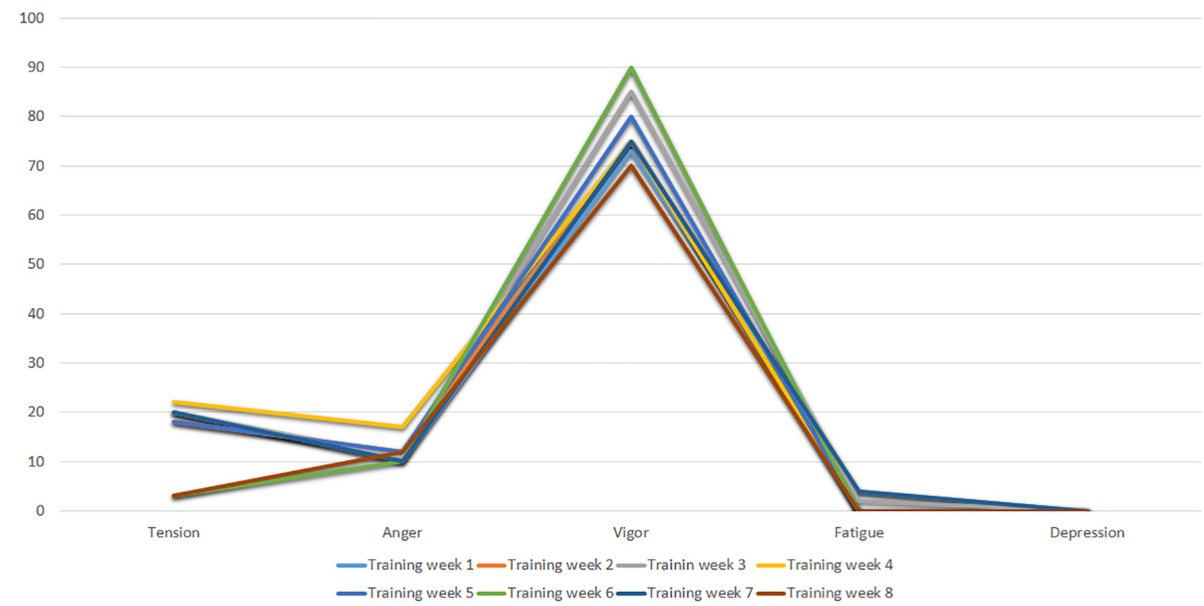

FIGURE 7
POMS profile of subject 2 after training weeks.

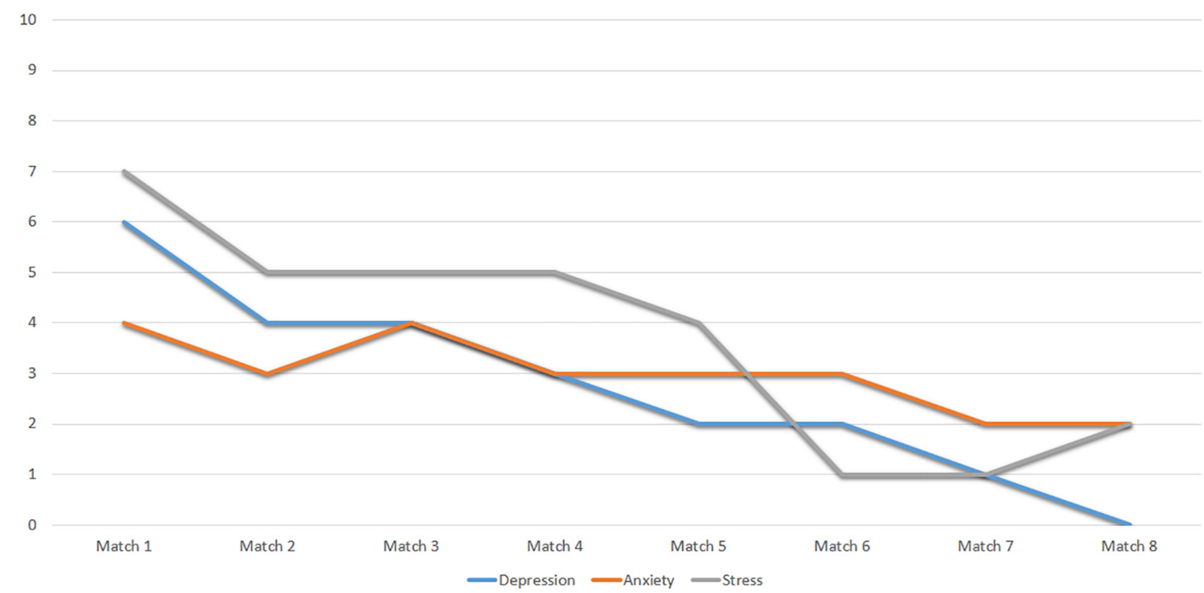

FIGURE 8
Scores of subject 2 to the subscales of the DASS-21.

where the Vigor factor is higher than the other factors and above the central value (50 points).

Finally, Figure 4 shows the scores obtained by Subject 1 in the DASS-21 subscales. It shows indicators of adequate mental health, with punctual severe anxiety peaks.

Subject 2 results

Figure 5 shows the scores obtained by Subject 2 on the PRIA throughout the assessment. The results show that until Match 3, the athlete's predisposition to return to sport was not sufficient or other types of complementary testing should be considered.

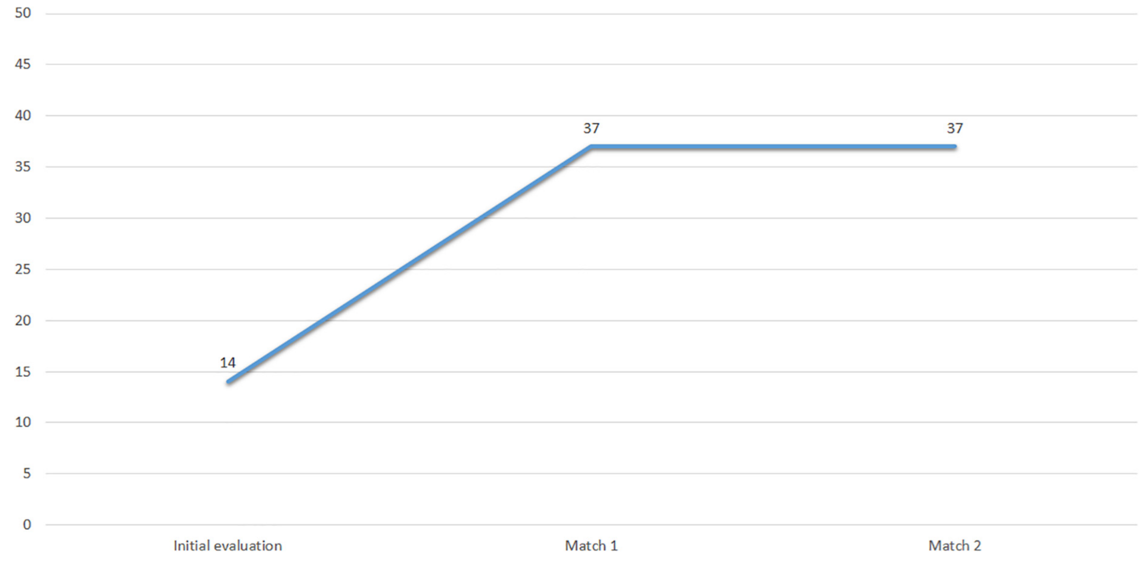

FIGURE 9
Subject 3 PRIA scores.

TABLE 5 Values in the POMS factors of Subject 3 after the matches.

Time of evaluation	Tension	Anger	Vigor	Fatigue	Depression
Match 1	50	46.8	40	55	55
Match 2	16.7	12.5	85	0	0
Match 3	12.5	9.4	80	0	0

TABLE 6 Values in the POMS factors of Subjetc 3 after training.

Time of evaluation	Tension	Anger	Vigor	Fatigue	Depression
Training week 1	16.7	15.6	85	45	0
Training week 2	16.7	15.6	85	5	0

From Match 4, the scores show adequate psychological predisposition to return to sport with some guarantees.

Table 3 shows the values of the POMS factors of Subject 2 in the nine recordings evaluated after the matches.

Next, Figure 6 shows the mood profiles of Subject 2 after the competition (Match 1 to Match 9). The results of Figure 6 show that Subject 2 gradually adopts an iceberg mood profile throughout the evaluation period. In this sense, the profile is characterized by low scores on the Tension, Anger, Fatigue and Depression factors. Vigor shows values above 50 (mean) in all the evaluated recordings.

Table 4 shows the scores that Subject 2 obtained on the POMS factors in the nine shots evaluated weekly after training.

Figure 7 shows the profiles of Subject 2 after training (Training week 1 to Training week 8). The results of the following Figure show that Subject 2 has a good pre-competitive mood profile, which is consistent with the iceberg profile. It shows an adequate state of coping with the competition, where the Vigor factor is above the central value (50 points) and the other factors are perfectly leveled for a correct athletic performance.

Finally, Figure 8 shows the scores obtained by Subject 2 on the DASS-21 subscales. The score profile shows indicators of adequate mental health, with slight expressions in all factors.

Subject 3 results

Figure 9 shows the scores obtained by Subject 3 at PRIA throughout the assessment. The results indicate that the psychological predisposition to return to sport was not sufficient in the first assessment, and although it has higher scores in Matches 1 and 2, the psychological predisposition of this athlete is uncertain and additional testing is needed to determine it.

Table 5 shows the values of the POMS factors of Subject 3 in the two recordings evaluated after the matches.

Figure 9 shows the profiles of Subject 3 in the three evaluation time points after the competition (Match 1 to Match 3).

Figure 9 shows a pre-competitive mood profile suitable for coping with competition. It shows an adequate iceberg profile in Matches 2 and 3. However, the mood profile of Match 1 is very inconsistent and shows almost an inverted iceberg profile, with a Vigor value lower than that of the other variables.

Table 6 shows the values of the POMS factors of Subject 3 in the two weekly post-training recordings evaluated.

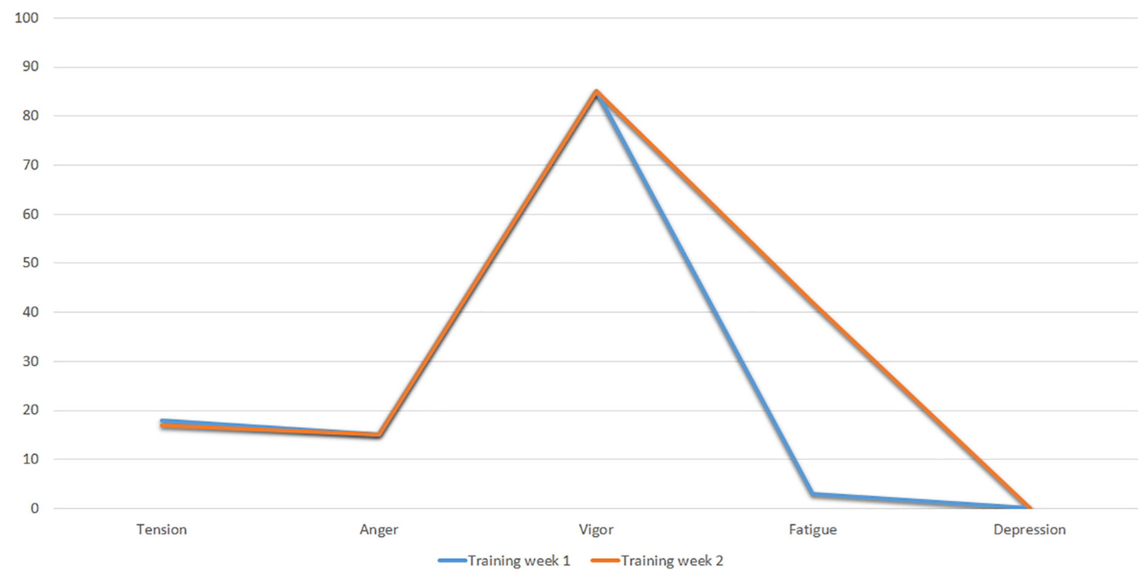

FIGURE 10
POMS profile of subject 3 after training weeks I and 2.

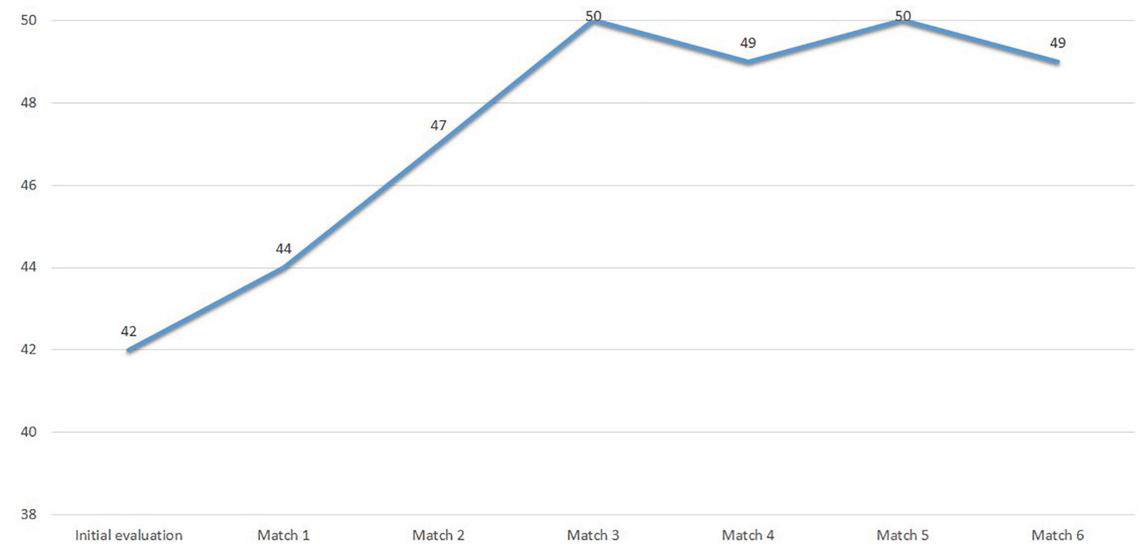

FIGURE 11
Subject 4 PRIA scores.

Figure 10 shows the profiles of Subject 3 at the two post-training evaluation times (Training Week 1 and Training Week 2). The results of Training Week 1 show a profile of pre-competitive mood suitable for competition, while Training Week 2 shows a Fatigue level higher than expected.

Finally, the scores obtained by Subject 3 on the DASS-21 subscales show a score of 2 points in Anxiety in Match 1 and 6 points in Match 2. In Depression, it shows a score of 5 in Match 1 and 2 points in Match 2. In stress, the athlete gets 5 points in Match 1 and 0 points in Match 2. The data show signs that this athlete's mental health is not adequate, as the depression, anxiety, and stress scores increase as the evaluation progresses.

Subject 4 results

Figure 11 shows the scores obtained by Subject 4 at PRIA. Scores above 40 indicate that the athlete is ready to return to sports with confidence.

TABLE 7 Values in the POMS factors of Subject 4 after the matches.

Time of evaluation	Tension	Anger	Vigor	Fatigue	Depression
Match 1	50	43.7	70	45	20
Match 2	8.3	21.8	90	0	0
Match 3	12.5	9.4	75	0	0
Match 4	12.5	12.5	90	0	0
Match 5	4.2	9.4	85	0	0
Match 6	4.2	12.5	60	0	0

Table 7 shows the scores of the POMS factors of Subject 4 in the seven recordings evaluated after the matches.

Next, Figure 12 shows the mood profiles of Subject 4 in Match 1 (Match 1 to Match 6). The pre-competitive mood profile from Matches 2 to 6 shows that it's consistent with the iceberg profile. Here, the Vigor factor is above the mean (50 points). However, the mood profile for Match 1 deviates slightly from the iceberg profile.

Table 8 shows the values of the POMS factors of Subject 4 in the seven shots evaluated weekly after training.

Figure 13 shows the mood profiles of Subject 4 in Training Weeks (Training Week 1 to Training week 7). Subject 4 shows an adequate pre-competitive mood profile in which the Tension, Anger, Fatigue and Depression factors have low values, while the Vigor factor has high values. Characteristic scores of the iceberg profile indicating an appropriate state of mind for the competition.

Finally, Figure 14 shows the scores obtained by Subject 4 on the DASS-21 subscales. The results show indicators of adequate mental health, although it is necessary to pay special attention to anxiety, which has high peaks at times.

Discussion

The aim of this study was to determine the relationship between the subjective psychological disposition of the athlete who has just overcome a sports injury and the nature of the mood profile and mental health in order to predict the risk of recurrence.

Subject 1 discussion

The obtained results showed that Subject 1 had the correct psychological disposition to resume sports. These results are consistent with other studies (Prapavessi, 2000; Neal et al., 2013; Clement et al., 2015; Caron et al., 2021) showing that athletes who adequately manage their emotions (Brewer et al., 2007; Glazer, 2009; García et al., 2015; Webster et al., 2018; Cools et al., 2021) are more successful in their athletic performance and return to RTP (De la Vega et al., 2013; Díaz et al., 2015; Horvath and Rothlin, 2018; Rollo et al., 2021). Similarly, the emotional profile of the iceberg described by Morgan (1980) has been gradually adopted, which is consistent with similar studies by other authors (Díaz et al., 2015; Andrade et al., 2016; Moreno-Tenas, 2018; Arroyo del Bosque et al., 2020; Palomo,

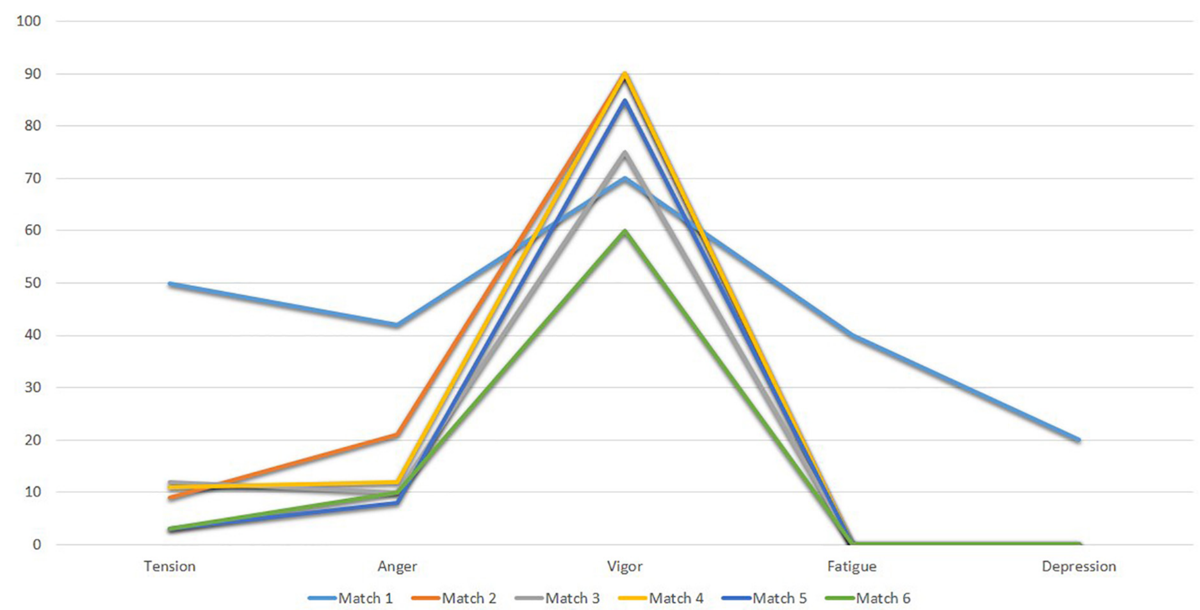

FIGURE 12
POMS profiles of subject 4 after matchs.

TABLE 8 Values in the POMS factors of Subject 4 after training.

Time of evaluation	Tension	Anger	Vigor	Fatigue	Depression
Training week 1	4.2	18.7	70	45	5
Training week 2	8.3	21.8	90	0	0
Training week 3	16.6	9.4	75	0	0
Training week 4	12.1	12.5	90	0	0
Training week 5	4.2	9.4	85	0	0
Training week 6	4.2	9.4	65	0	0
Training week 7	4.2	6.2	85	0	0

2020). Together with the low anxiety, stress and depression scores, this suggests that these are emotional scores associated with an effective mental health model to predict athletic success. Based on the existing literature indicating that a timely return to sports practise, a correct psychological predisposition to RTP, and appropriate emotional management prevent the possible ocurrence of recurrences, the data obtained were favorable for RTP and avoid future recurrences (Lu and Hsu, 2013; Neal et al., 2013; Roy et al., 2015; Gomez-Espejo et al., 2018; Moreno-Tenas, 2018; Green et al., 2020; Zhang et al., 2022).

Subject 2 discussion

The results indicated that further testing was needed to determine if the athlete was psychologically prepared for the RTP. However, the mood profile was consistent with the iceberg profile, which states that mood did not change prior to the competition because it was a healthy psychological state that was maintained both after the competition and after practices. These results are consistent with other studies (De la Vega et al., 2011; Díaz et al., 2015; Andrade et al., 2016; Moreno-Tenas, 2018; Arroyo del Bosque et al., 2020; Palomo, 2020). On this basis, and with low levels of anxiety, depression, and stress, it seems to show indicators of good mental health. Different studies have shown that negative emotions tend to decrease as the return to sport process progresses, while positive emotions tend to increase as the RTP process progresses (Lalín, 2009; Mainwaring et al., 2010; Olmedilla et al., 2014; García et al., 2015; Rossi et al., 2021). Therefore, it is possible that she did not return to the sport with complete certainty, but that her perceptions changed as the competition evolved.

Subject 3 discussion

The results of the PRIA indicated that the athlete felt psychologically unable to return to sport or that further complementary testing was needed to confirm this. In addition, the inverted iceberg profile he showed in Game 1, along with the increase in anxiety and stress scores over the course of the evaluation, indicated that the athlete was not ready to return to the sport. With this in mind, and considering that positive mood states serve as indicators of protection against sports injuries and recurrences (Rozen and Horne, 2007), the likelihood of this athlete relapsing is high.

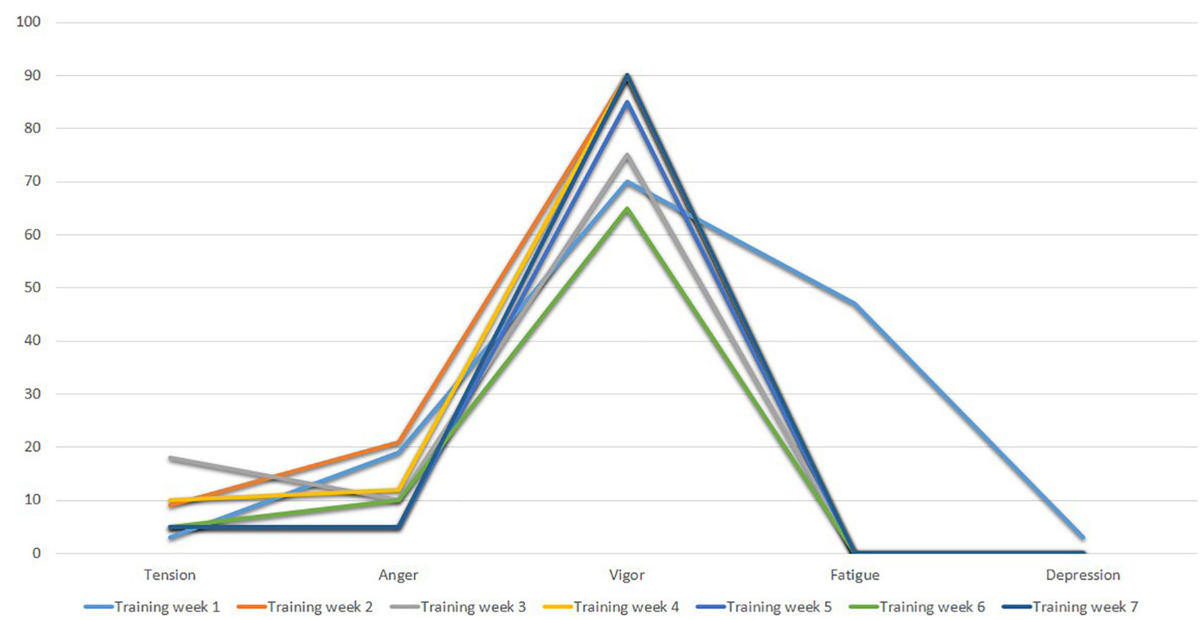

FIGURE 13
POMS profiles of subject 4 after training weeks.

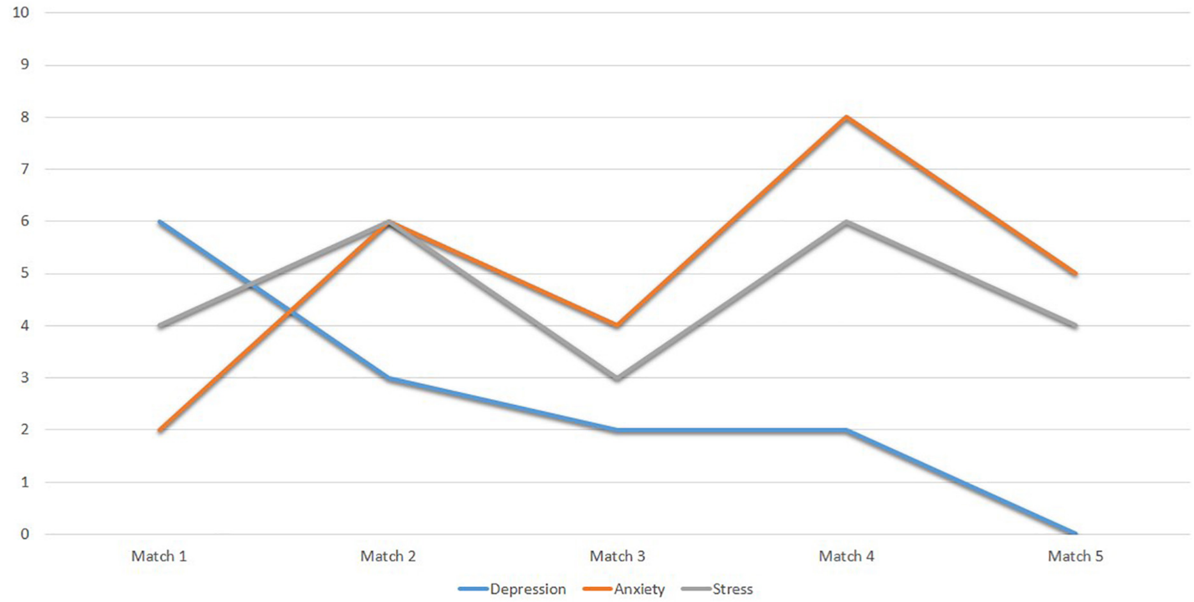

FIGURE 14
Scores of subject 4 to the subscales of the DASS-21.

Subject 4 discussion

He demonstrated adequate psychological predisposition to return to sport safely and showed a good mood profile consistent with the iceberg profile. The mood profile for Match 1 and Training Week 1 did not show the iceberg profile as strongly. In the first case, high scores were shown in the Tension, Anger and Fatigue factors (without exceeding the central point), whereas in training, high scores were reported in the Fatigue factor. These results are consistent with those of Alzate et al. (2004), who demonstrated that athletes increasingly adopted an iceberg profile as the recovery process progressed (Abenza et al., 2009), highlighting that the emotional response to sports injury is not a static phenomenon and that the effectiveness of sports rehabilitation treatments can be enhanced by formal or informal assessments of changes in the athlete's mood during the rehabilitation period (Arroyo del Bosque et al., 2020). Finally, the low scores of the depression factor decreased as the assessment progressed, while, the scores for anxiety and stress fluctuated. These results may be due to the fact that, as suggested by Walker et al. (2010), the term anxiety or stress in relation to a new injury would be more appropriate to refer to the emotional response traditionally known as fear of a new injury, because from a psychological perspective, the RTP phase can be particularly challenging as anxiety and stress may resurface once the athlete has been cleared for RTP (Clement et al., 2015; Green et al., 2020).

Previous literature has shown that returning athletes to sport before they are psychologically ready can lead to fear, anxiety, stress, recurrence, second injuries, depression, and decreased performance (Ahern and Lohr, 1997; Clement et al., 2013; Rossi et al., 2021).

Future lines of research

This study has some limitations that should be considered. First, the sample is insufficient and geographically very limited, since it was conducted only in one autonomous community. The fact that a sample of soccer players from different areas (11-a-side soccer and futsal) was studied. While there are enough studies for 11-a-side soccer, this is not the case for futsal, so it could be very interesting to open a line in this field. In this sense, it seems reasonable to use samples as homogeneous as possible. Also, the exceptional situation imposed by COVID-19, which forced the interruption of competitions and training, forced to stop the evaluation process. In conclusion and considering these limitations, it would be necessary to consider in future researches the continuity of this work and try to expand the study population and its homogeneity. In addition, it would be interesting to monitor the athlete during his RTP process to ensure an adequate return to sports practice and to check if recurrences occur.

At an applied level, the results presented provide new information for the design of intervention programs aimed at coaches (Sousa et al., 2007; Soriano et al., 2014) and psychologists (De la Vega et al., 2011; Díaz et al., 2015; Moreno-Tenas, 2018; Arroyo del Bosque et al., 2020; Caron et al., 2021). Proper reading of moods as well as anxiety, stress, depression, and psychological predisposition can help sport professionals determine the right time for RTP. In this way, this work calls for the attention of technicians, coaches and clubs to integrate the psychological variables in their training programs, just as they train the physical, conditioning, technical and tactical aspects and take measures that help the injured athlete to develop a realistic and positive attitude toward rehabilitation as a guarantee for a successful recovery.

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 in the article/**Supplementary material**.

Ethics statement

The studies involving human participants were reviewed and approved by Ethics Committee of the University of Murcia. The patients/participants provided their written informed consent to participate in this study.

Author contributions

VG-E, AO, and EO designed the study as a whole. AO designed the questionnaires' protocol and VG-E adapted them in the online version. VG-E prepared the draft of the introduction, with all the coauthors contributing to the revision and final version. VG-E carried out the data collection. EO was in charge of the statistical analyzes. LA-C and AG-M prepared the first draft of the discussion, with all the co-autothors contributing to the final version and revisions. All authors contributed to the article and approved the submitted version.

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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.905816/full#supplementary-material

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TYPE Brief Research Report
PUBLISHED 28 September 2022
DOI 10.3389/fpsyg.2022.957281

Boosting effect of regular sport practice in young adults: Preliminary results on cognitive and emotional abilities

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Several studies have shown that physical exercise (PE) improves behavior and cognitive functioning, reducing the risk of various neurological diseases, protecting the brain from the detrimental effects of aging, facilitating body recovery after injuries, and enhancing self-efficacy and self-esteem. Emotion processing and regulation abilities are also widely acknowledged to be key to success in sports. In this study, we aim to prove that regular participation in sports enhances cognitive and emotional functioning in healthy individuals. A sample of 60 students (mean age = 22.12; SD = 2.40; M = 30), divided into sportive and sedentary, were subjected to a neuropsychological tests battery to assess their overall cognitive abilities (Raven's Advanced Progressive Matrices, APM), verbal and graphic fluency (Word Fluency Task and modified Five Point Test, m-FPT), as well as their emotional awareness skills (Toronto Alexithymia Scale, TAS-20). Our results showed that sportive students performed better than sedentary ones in all cognitive tasks. Regarding emotional processing abilities, significant differences were found in the TAS-20 total score as well as in the Difficulty Describing Feelings (DDF) subscale and the Difficulty Identifying Feeling (DIF) subscale. Lastly, gender differences were found in the External-Oriented Thinking (EOT) subscale. Overall, our findings evidence that PE has positive effects on cognitive functioning and emotion regulation, suggesting how sports practice can promote mental health and wellbeing.

KEYWORDS

sport, cognition, emotion regulation, physical activity, alexithymia

OPEN ACCESS

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

RECEIVED 30 May 2022
ACCEPTED 29 August 2022
PUBLISHED 28 September 2022

CITATION
Passarello N, Varini L, Liparoti M, Troisi Lopez E, Sorrentino P, Alivernini F, Gigliotta O, Lucidi F and Mandolesi L (2022) Boosting effect of regular sport practice in young adults: Preliminary results on cognitive and emotional abilities. *Front. Psychol.* 13:957281.
doi: 10.3389/fpsyg.2022.957281

Introduction

Physical exercise (PE) is defined as a form of physical activity that is planned, structured, and repetition-based, with the goal of improving or maintaining individual components of physical fitness. PE is defined as a sports activity when an individual systematically trains under expert supervision for a specific technical gesture (Mandolesi et al., 2018).

A substantial body of evidence has shown that PE induces a brain plasticity phenomenon (Fernandes et al., 2017; Mandolesi et al., 2018) that represents the ability of the brain to reorganize and change after proper stimulation, thus improving its performance (Serra et al., 2011; Mandolesi et al., 2017; Gelfo et al., 2018).

For a few years now, the beneficial effects of PE on mood and cognition across the life span have become a topic of interest. Much evidence suggests that PE improves behavior and cognitive functioning, reducing the risk of various neurological diseases, protecting the brain from the detrimental effects of aging, facilitating body recovery after injuries, and enhancing self-efficacy and self-esteem (Lista and Sorrentino, 2010; Basso and Suzuki, 2017). Cross-sectional studies have shown that PE boosts memory abilities, attentional processes' efficiency, and executive functioning (Colcombe and Kramer, 2003; Grego et al., 2005; Pereira et al., 2007; Chieffi et al., 2017; Erickson et al., 2019). Specifically, executive functions are frequently targeted for PE studies, as they play a crucial role in both mental and physical health (Davis et al., 2011), success in school, and quality of life (Bailey, 2007), as well as social, cognitive, and psychological development (Diamond, 2016). Nonetheless, inhibition control, working memory, and cognitive flexibility are considered to be key abilities for sports practice (Ludyga et al., 2016).

Emotion processing and regulation skills are also widely acknowledged to be key to success in sports (Friesen et al., 2013). The ability to process and regulate emotions successfully is regarded by many as an important psychological skill in sportive individuals (Jodat et al., 2015). Several studies demonstrate the enormous benefits of structured and constant sports training in terms of improving motivation and emotional wellbeing (Ghasempour et al., 2013; Behroozi and Abdimoghadam, 2014). The ability to successfully process and regulate our emotions requires emotional awareness. In some individuals, this ability is deficient, resulting in difficulties identifying, describing, and analyzing what they are experiencing emotionally (Passarello et al., 2021). Considering the importance of emotional regulation in everyday life, constant and structured PE seems to be a protective factor for this difficulty (Jodat et al., 2015). In spite of this, there are still few studies that examine the correlation between sport and emotional regulation.

In this study, we aim to demonstrate that regular participation in sports can lead to an improvement in cognitive and emotional functioning. To do this, a sample of 60 students (mean age = 22.12, SD = 2.40), divided into sportive and sedentary, were subjected to a neuropsychological tests battery to assess their overall cognitive abilities, and verbal and graphic fluency (Raven Advanced Progressive Matrices, APM; World fluency test; modified-Five Points Test, m-FPT), as well as their emotional awareness skills (Toronto Alexithymia Scale, TAS-20). We hypothesized that sportive students would demonstrate enhanced cognitive abilities, along with better skills at recognizing and describing their emotions, compared to sedentary students.

Materials and methods

Participants

We tested 60 students from the University of Naples "Federico II." A survey was conducted to ask students if they practice any type of sport, how long they had been practicing it, how often, and at what intensity. From the output of this survey, we selected our sample, and we sorted the students into two groups as follows: Sportive = 15 females (mean = 22; SD = 2.76) and 15 males (mean = 22.18; SD = 3.15); Sedentary = 15 females (mean = 23; SD = 2.04) and 15 males (mean = 21.30; SD = 1.26). Participants who had practiced sports for at least 2 years with a frequency of 3 times a week and with a moderate level of intensity belonged to the sportive group. All participants were in good health. Inclusion criteria were normal or corrected-to-normal vision and right-handedness. Alternatively, exclusion criteria comprised the current or past presence of psychopathology, psychiatric, neurological, or motor disorders, or other medical illness. The participants were voluntarily enrolled after written informed consent was obtained. The study was approved by the Local Ethics Committee of the University of Naples "Federico II" (protocol number: 12/2020) and was carried out in accordance with the Declaration of Helsinki.

Neuropsychological assessment

To evaluate the typical development of all the participants, Raven's Advanced Progressive Matrices (APM) (Raven, 1962) were administered. Specifically, we used set 1 consisting of the first 12 matrices. To complete each item, one must replace the missing part of a model, according to a criterion of increasing difficulty. Model figures consist of graphic patterns that change from left to right and from top to bottom; the subject must understand the underlying logic and apply it in order to come up with the solution. APM total score allowed us to assess abstract reasoning and global cognitive functioning.

Verbal fluency was also assessed through word fluency test (Carlesimo et al., 1996). In this test, participants were asked to produce as many words as possible, beginning with specified letters of the alphabet (A; F; S), in a limited time interval of 60 s. Total word produce, word errors (i.e., word beginning with a different letter), and word repetitions were analyzed.

The five-point test (FPT) is a highly reliable nonverbal measure of executive functioning, assessing the graphic-figural fluency of participants (Fernandez et al., 2009). In fact, it measures the ability of an individual to produce geometric drawings or unique figures within a given time interval (3 min) (Cattelani et al., 2011). The modified FTP version (m-FTP) consists of an A4 sheet with 40 square matrices, each containing five dots; four of them are placed at the vertices and one is placed in the middle. Participants must connect two or more dots in each square with straight lines. Additionally, they must not repeat the same shape two times and must not draw lines that do not connect the dots. Through this, we can examine three subdomains of executive functions, namely, flexibility, rule breaking, and strategic performance. The following parameters were evaluated: (A) total drawings: number of total drawings made in 3 min; (B) drawings with errors: number of drawings breaking the rules and/or repeating previously drawn shapes; (C) error index: number of drawings with errors divided by the number of total drawings multiplied by 100; (D) number of unique drawings: calculated by subtracting the number of drawings with errors from the number of total drawings; and E) strategy index: number of drawings with strategy divided by number of unique drawings. All the neuropsychological instruments used are validated for the Italian language and culture (Di Fabio and Clarotti, 2007; Carlesimo et al., 1996; Cattelani et al., 2011).

Toronto alexithymia scale (TAS-20)

The TAS-20 (Bagby et al., 1994) is a 20-item self-report test considered to be the most reliable self-assessment questionnaire for measuring alexithymia, an affective-cognitive disorder characterized by difficulty in identifying and describing own emotions and in being interested in understanding those of others (Nemiah and Sifneos, 1970). TAS-20 consists of three subscales, each representing one aspect of alexithymia: the Difficulty Describing Feelings (DDF) subscale consisted of five items (2, 4, 11, 12, and 17); the Difficulty Identifying Feeling (DIF) subscale consisted of seven items (1, 3, 6, 7, 9, 13, and 14); and the External-Oriented Thinking (EOT) subscale, measuring the tendency of individuals to focus their attention externally, consisted of eight items (5, 8, 10, 15, 16, 18, 19, and 20).

Participants respond to TAS-20 using a 5-point Likert scale, where 1 indicates strongly disagree and 5 indicates strongly agree. Items 4, 5, 10, 18, and 19 are negatively keyed. Alexithymia scores are determined by summing responses to all 20 items, while scores for each of the subscales are determined by summing the responses in each scale. Scores of 61 or higher are considered alexithymic; scores of 50 or lower are considered non-alexithymic, with a borderline between 50 and 60. In this study, we used the Italian standardized and adapted version of the TAS-20 (Bressi et al., 1996).

TABLE 1 The 2 × 2 ANOVA outputs on advanced progressive matrices (APM).

Factors	$F_{1,56}$	p	p Tukey
Sport	5.13	0.02*	0.02*
Sex	0.01	0.90	0.90
Sport*Sex	1.25	0.28	0.28

*$p \leq 0.05$.

Statistical analyses

All statistical analyses were conducted with the JASP 0.16.1.0 software. The 2 × 2 ANOVA was used to analyze the effect of gender (males, females) and sport practice (sportive, sedentary) on neuropsychological tests (APM, word fluency, and m-FPT) and TAS-20. $p \leq 0.05$ were considered statistically significant. *Post-hoc* comparisons were conducted through Tukey's test.

Results

Neuropsychological assessment

The 2 × 2 ANOVA outputs on APM are shown in Table 1, while word fluency and m-FPT outputs are shown in Figures 1, 2.

Significant differences were found in APM score ($F_{1,56} = 5.14$; $p = 0.03$), word production ($F_{1,56} = 52.62$; $p \leq 0.001$), and word repetition ($F_{1,56} = 14.60$; $p \leq 0.001$) for sport factor. *Post-hoc* comparisons revealed significant difference between sportive students and sedentary students in APM score (mean sportive = 10.80; mean sedentary = 10.16), word production (mean sportive = 50.70; mean sedentary = 36.07), and word repetition (mean sportive = 5.40; mean sedentary = 2.30). As for word errors, we found significant differences for sex factor ($F_{1,56} = 6.20$; $p = 0.02$). *Post-hoc* comparisons on word errors revealed significant differences between males and females (mean males = 1.43; mean females =0.77).

Several results were found among m-FPT parameters. The 2 × 2 ANOVA revealed significant differences in the total drawing for sport factor ($F_{1,56} = 31.22$; $p \leq 0.001$) (Figure 2A). *Post-hoc* comparisons revealed a significant difference between sportive students and sedentary students in total drawings productions (mean sportive = 51.43; mean sedentary = 34.77). No significant

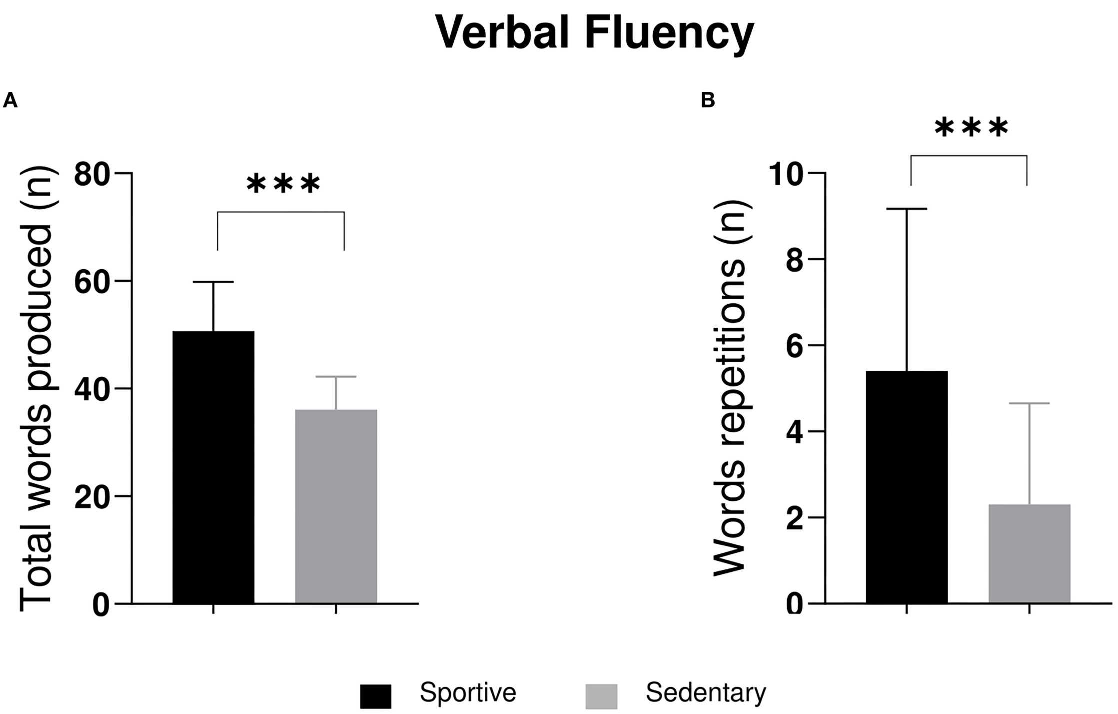

FIGURE 1
The 2 × 2 ANOVA significant outputs on **(A)** total words produced and **(B)** words repetitions. ***$p \leq 0.001$.

differences were found for sex ($F_{1,56} = 0.36$; $p = 0.55$) or interception ($F_{1,56} = 0.29$; $p = 0.59$).

Moreover, significant differences were found in total unique drawings for the sport factor ($F_{1,56} = 82.30$; $p \leq 0.001$) (Figure 2B). *Post-hoc* comparisons revealed a significant difference between sportive students and sedentary students in unique drawings productions (mean sportive = 47.30; mean sedentary = 29.60). No significant differences were found for sex ($F_{1,56} = 0.49$; $p = 0.49$) or interception ($F = 0.25$; $p = 0.62$). No significant differences were found in the error index for sports, sex, or interception.

Finally, significant differences were found in strategy for sport factor ($F_{1,56} = 7.15$; $p = 0.01$) (Figure 2C). *Post-hoc* comparisons revealed a significant difference between sportive students and sedentary students in strategy use for drawing (mean sportive = 0.14; mean sedentary = 0.10). No significant differences were found for sex ($F_{1,56} = 0.19$; $p = 0.66$) or interception ($F_{1,56} = 1.66$; $p = 0.20$).

TAS-20

Among our 60 participants, only two were found to be alexithymic with an average score of 65. The rest of the group obtained an average score of 44.93. Twenty of the remaining participants obtained an overall score that falls in the critical range of 50–60 (Supplementary Table 1).

As for TAS total score, the 2 × 2 ANOVA revealed a significant difference for sport factor ($F_{1,56} = 6.01$; $p = 0.02$) (Figure 3A). *Post-hoc* comparisons lower alexithymic score in sportive students rather than sedentary students (mean sportive = 42.70; mean sedentary = 48.50). No significant differences were found for sex ($F_{1,56} = 0.18$; $p = 0.67$) or interception ($F_{1,56} = 0.26$; $p = 0.61$).

TAS factor DIF was significantly different for sport factor ($F_{1,56} = 4.52$; $p = 0.04$) (Figure 3B). *Post-hoc* comparisons revealed minor difficulties in identifying feelings in sportive students rather than sedentary students in total score (mean sportive = 11.70; mean sedentary = 13.90). No significant differences were found for sex ($F_{1,56} = 2.20$; $p = 0.14$) or interception ($F_{1,56} = 1.07$; $p = 0.80$).

TAS factor DDF was also significantly different for sport factor ($F_{1,56} = 4.37$; $p = 0.04$) (Figure 3C). *Post-hoc* comparisons revealed minor difficulties in describing feelings in sportive students rather than sedentary ones (mean sportive = 15.87; mean sedentary = 18.73). No significant differences were found for sex ($F_{1,56} = 48.60$; $p = 0.19$) or interception ($F_{1,56} = 72.60$; $p = 0.11$). No significant differences were found in EOT_A for sport, sex, and interception.

Finally, TAS factor EOT_B was significantly different for sex factor ($F_{1,56} = 7.78$; $p = 0.007$) (Figure 3D). *Post-hoc*

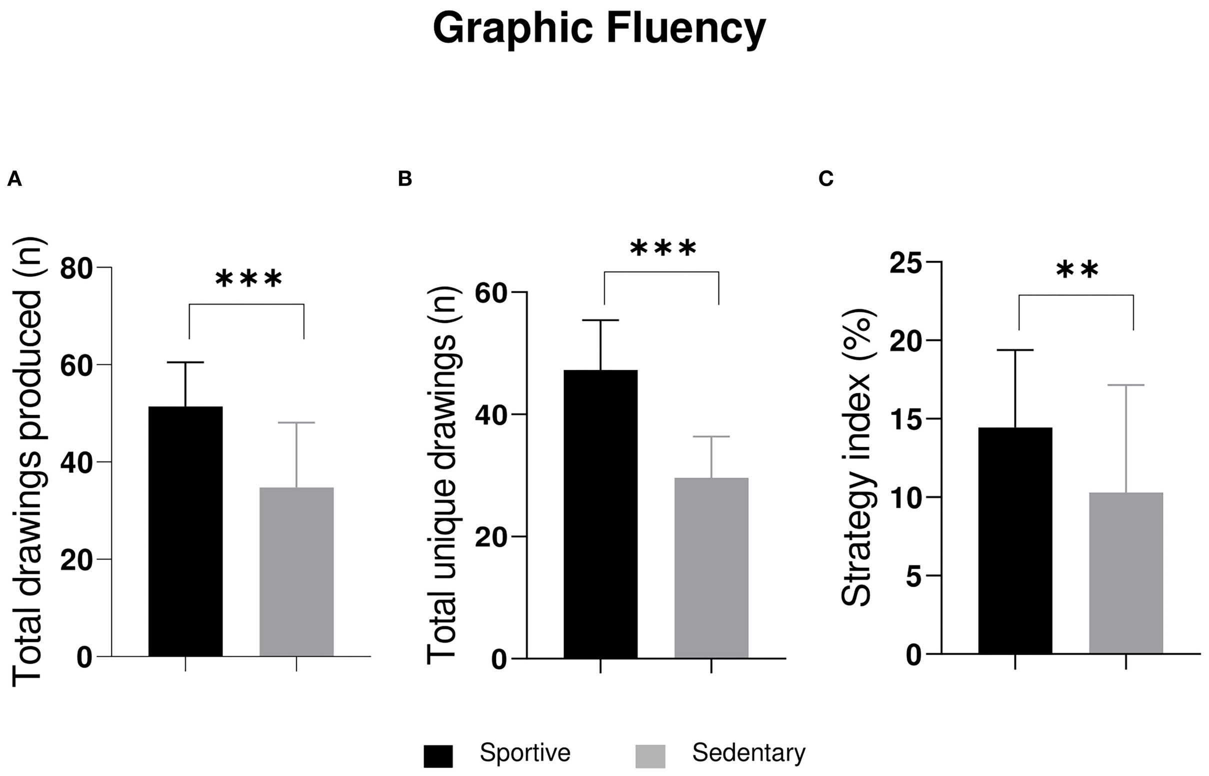

FIGURE 2
The 2 × 2 ANOVA significant outputs on **(A)** total drawings produced, **(B)** total unique drawings, and **(C)** strategy index. **$p \leq 0.01$; ***$p \leq 0.001$.

comparisons revealed more external-oriented thinking in males rather than females (mean males = 7.37; mean sedentary = 5.80). No significant differences were found for sport ($F_{1,56}$ = 0.09; $p = 0.77$) or interception ($F_{1,56} = 0.08$; $p = 0.76$).

Discussion

In accordance with our hypotheses, our results showed that sportive students performed better than sedentary ones on tasks of global intelligence, verbal and graphic fluency, and emotional awareness. In spite of our sample consisting of students with typical development, as evidenced by the normal Raven matrices (APM) scores, we found that the sportive group performed better than the sedentary group in APM. Several studies showed that both children and young adults' experiences in sport and PE contribute to the mental acuity, skills, and strategies that are important for navigating challenges faced across the life span (Donnelly et al., 2016). Neuroscience advances have enabled significant progress in linking PE to cognitive performance, as well as to brain structure and function (Mandolesi e al., 2018). It was found that PE could determine structural changes in gray matter volume in frontal and hippocampal regions and enhance the release of neurotrophic factors, such as peripheral BDNF (Serra et al., 2011; Mandolesi et al., 2018). These effects are reflected on cognitive functioning. In our study, sportive students performed better in word fluency task, producing more words than sedentary students. Further, aerobic exercise improves verbal fluency among healthy elderly (Bullo et al., 2015). This evidence validates the selective improvement hypothesis, which states that aerobic PE selectively improves brain activities associated with the frontal and prefrontal regions (Weinstein et al., 2012; Nocera et al., 2015, 2020). Indeed, PE is associated with high scores on tests that evaluate executive functioning (Verburgh et al., 2014; de Greeff et al., 2018; Xue et al., 2019; Serra et al., 2021). In our study, it is important to note that the m-FPT provides insight into executive functioning (Weinstein et al., 2012), and also in this test, we found significant differences in favor of sports students. It is important to note that, among our sample of sportive students, more repetitions of words were also recorded. However, the increased use of repetition by sportive students appears to be in contrast to the results discussed so far; this was only true for verbal fluency and not for graphic fluency. Sportive students were in fact more productive than the sedentary ones in the m-FPT, but more importantly, they produced more unique designs and used strategies more often. This dissociation between verbal and visuospatial abilities (including graphic fluency competencies)

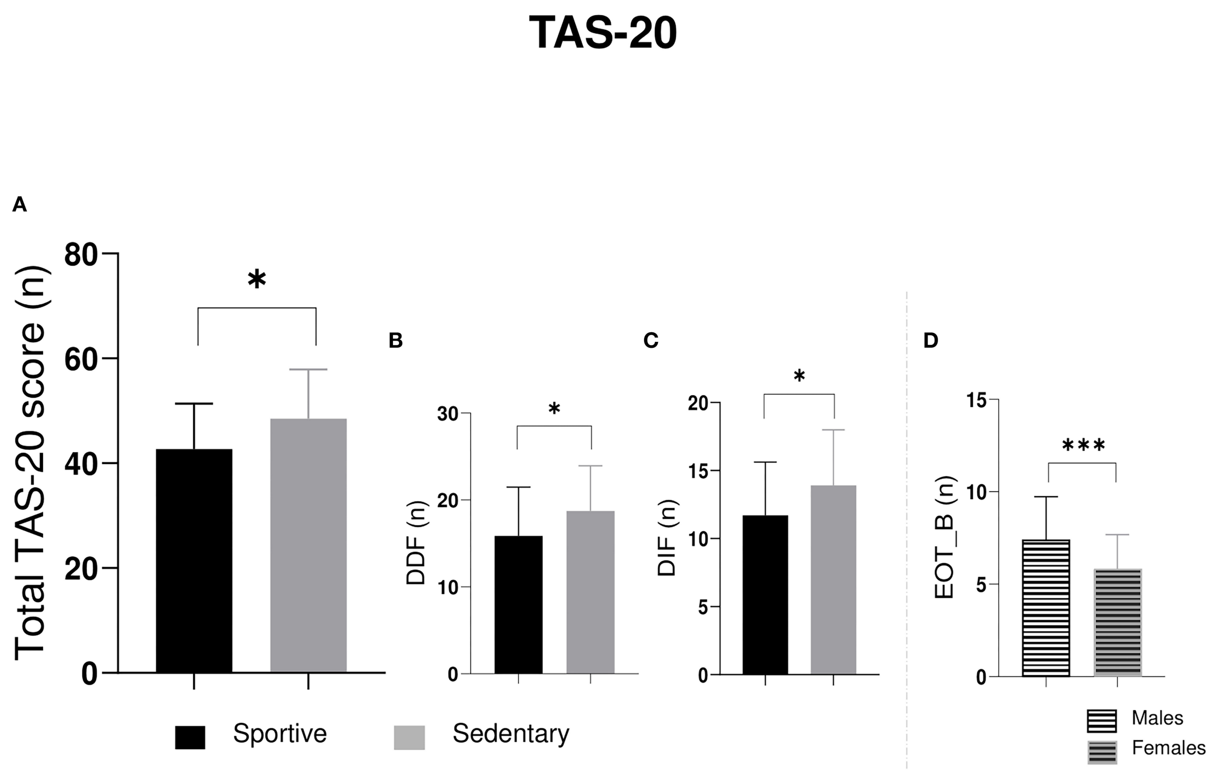

FIGURE 3
The 2 x 2 ANOVA significant outputs on **(A)** total TAS-20 score, **(B)** DIF factor, **(C)** DDF factor, and **(D)** EOT_B factor. DIF, difficulty identifying feelings; DDF, difficulty describing feelings; EOT, external-oriented thinking. *$p \leq 0.05$; ***$p \leq 0.001$.

has long been associated with a hemispheric lateralization (Lardone et al., 2021). Several studies have shown that performance in verbal fluency task was associated with increased left prefrontal activity, whereas performance in visuospatial fluency task was associated with increased bilateral prefrontal activity (Marin et al., 2017; Cipolotti et al., 2020). An interesting work (Elfgren and Risberg, 1998) takes also in account the cognitive strategy used during fluency tasks. Participants were asked to explain the type of strategy they used to solve both verbal and visuospatial task: they could have used a purely verbal strategy (i.e., think about nameable objects), a purely visual strategy (i.e., use visual imagery), or a mix of the two. In the visuospatial fluency task, participants used more mixed strategies, whereas in the verbal fluency task, they used mixed and verbal strategies. Both in visuospatial and verbal fluency tasks, the application of mixed strategies was associated with increased bilateral activity in the prefrontal cortex. Meanwhile, the application of verbal strategies only was associated with an increase in activity just in the left dorsolateral prefrontal cortex. We can speculate that PE enhances hemispheric lateralization, improving both verbal skills linked to left-hemisphere activity and visuospatial skills that appear to be linked to bilateral activity (Wang et al., 2016). However, it does not have a specific effect on the left-hemisphere-related activity required to improve the use of appropriate strategies to solve verbal fluency tasks. Although more results are needed to confirm the latter hypothesis, we can conclude that regular practice of a sport improves overall cognitive functioning. Additionally, our results showed that sportive students were more aware of their own emotions than sedentary ones, displaying fewer difficulties in identifying and describing their own feelings. PE beneficial effects on emotional processing has been widely reported. Epidemiological studies have shown PE soothing effects on depression (Mammen and Faulkner, 2013) and anxiety (Knapen et al., 2009). Numerous studies have shown that most aerobic exercises, regardless of their type, lead to an enhanced positive mood afterward (Fernandes et al., 2017).

Alexithymia, or "no words for feelings," is a personality trait that is associated with difficulties in emotion recognition and regulation (Swart et al., 2009). In sport, it is mostly associated with disorders, such as anxiety, depression, overtraining (burnout), addiction, and risky sports behavior (Woodman et al., 2009). However, some studies have proved that sport practice can improve emotional recognition and regulation, and accordingly, fewer alexithymic traits can be found in sportive individuals (18). These data agree with our result in which sportive students have lower scores on TAS-20 (Figure 3A). It has been reported that sport practice had several benefits for students, including less difficulty in "identifying and distinguishing physical feelings and sensations," better sleep, and higher scores on happiness and life satisfaction (Manfredi, 2022). Sportive students also showed more external-oriented thinking than sedentary ones. The results of our work do not directly confirm this finding, but they do detect a gender difference regarding factor 3B of the TAS-20 (external-oriented thinking). Specifically, males tend to use more external-oriented thinking than females, regardless of whether they practice sport. Based on this finding, it may explain why some scientific evidence suggests that alexithymia is associated with increased athletic activity, especially in high-risk sports. Although it is true that there is a greater prevalence of alexithymia in high-risk sports contexts (Woodman et al., 2009; Woodman and Welch, 2021), these data may also be biased due to gender. It is possible that the gender differences would be marked mainly in the verbalization of emotions and in external-oriented thinking, since both of these dimensions of alexythimia are more frequently associated with males, due to social desirability bias (Proença Lopes et al., 2022a,b). Since our sample was balanced by gender, we can speculate that sportive individuals are less alexithymic, and instead, the higher prevalence of alexithymia in high-risk sporting contexts is probably due to gender; however, more evidence is needed.

The results from our study agree with the majority of studies on PE and its effect on psychological wellbeing (Ghasempour et al., 2013). As pointed out by these studies, while practicing a sport, individuals not only acquire physical growth but also experience personal, mental, and emotional growth as well. Moreover, by creating a context for increasing their sense of empowerment and self-worth, sport's environment prevents young adults to develop psychological, emotional, and affective problems (e.g., alexithymia and its components). Sport practice can also improve positive attitudes and change negative beliefs and dysfunctional views of people's lives and their surroundings (Cox, 2012). To get the full picture, we also need to assess some socio-psychological factors that can contribute to the cognitive functioning differences between those who practice sports and those who lead a sedentary lifestyle. Indeed, the characteristics of sportive populations often include a favorable economic condition along with goal-directed behavior or proactivity that differ from those of sedentary ones (Hallmann and Breuer, 2014; Lucia et al., 2021). While these socio-economic factors have not been examined in this preliminary study, they provide a reflection for future research which will allow us to study the specific weights of each psychological factor involved in defining a specific "cognitive sportive profile." There are, however, other limitations to our results, making them even more preliminary. A larger sample is needed to further strengthen the association between sport practice and psychological wellbeing, which also allows us to consider individual and gender-related differences. It should be noted that most of our sample was composed of amateur tennis players who belonged to the same sports association. Since we know that different types of physical activity have different effects on our cognitive abilities, it would be worthwhile to investigate the effects of other sports disciplines. According to Mandolesi et al. (2018), the benefits of PE on cognitive functioning and wellbeing are different depending on whether the activity is performed aerobically or anaerobically. Moreover, there is a major difference between chronic and acute PE, with chronic aerobic exercise being mostly associated with structural and functional neuroplastic changes along with enhanced cognitive functions (Colcombe et al., 2006; Mandolesi et al., 2017). Finally, our study was conducted following COVID-19 lockdown during which our students continued to train and to resume outdoor physical activity once possible. It could be useful to know whether PE's beneficial effects are sustained if physical activity is interrupted for an extended period.

In conclusion, our preliminary results show that regular exercise and participation in sport can positively affect cognitive and emotional functioning. Our sportive students performed better than sedentary students in terms of global intelligence, graphic and verbal fluency, as well as recognizing and describing emotions. It can be concluded that the promotion of PE in young and at-risk populations is an important priority for the promotion of psychological wellbeing, considering its beneficial function.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by Local Ethics Committee of the University of Naples Federico II (protocol number: 12/2020). The patients/participants provided their written informed consent to participate in this study.

Author contributions

NP, LV, and ML performed the research. NP, ET, and PS analyzed the data. NP, FA, OG, FL, and LM wrote the manuscript. All authors designed the research, read, revised, and approved the final manuscript.

Funding

This research was supported by funding from the Department of Humanities, University of Naples Federico II (Fondi ricerca dipartimentale 70%, 2020 and 2021) to LM.

Acknowledgments

We would like to thank Stefania Crimaldi, the amateur athletes of Tennis Club Petrarca, and the students of the Department of Humanities, University of Naples Federico II for making this study possible.

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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.957281/full#supplementary-material

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frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 08 November 2022
DOI 10.3389/fpsyg.2022.1006289

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OPEN ACCESS

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

RECEIVED 29 July 2022
ACCEPTED 20 October 2022
PUBLISHED 08 November 2022

CITATION
Tian H, Zhou W and Qiu Y (2022) The mediating role of psychological commitment between recreation specialization and life satisfaction: Evidence from Xiamen Marathon runners.
Front. Psychol. 13:1006289.
doi: 10.3389/fpsyg.2022.1006289

The mediating role of psychological commitment between recreation specialization and life satisfaction: Evidence from Xiamen Marathon runners

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Although previous research spared no efforts to explain the life satisfaction of marathon runners, little was known about the relationship between recreation specialization (RS), life satisfaction (LS), psychological commitment (PC), and social support (SS). This study examines (i) how the dimension of RS (i.e., behavior, cognition, and affect) influences runners' PC and LS, and (ii) the mediating effects of PC and the moderating effects of SS on the relationship between behavior, cognition, affect, and LS. The results showed that behavior (β=0.15, p<0.01), cognition (β=0.35, p<0.001), affect (β=0.28, p<0.001), and PC (β=0.59, p<0.001) had significant and positive impacts on runners' LS; PC (Indirect path coefficient=0.09~0.20) mediated the relationship between the dimensions of RS and LS. In addition, the results also confirmed the moderating effects of SS (β=0.10, p<0.05) between affect dimension and LS. These findings offered more evidence for understanding how RS dimensions and PC influence runners' LS. Future research should integrate runner's leisure experiences to better understand the results revealed in this study.

KEYWORDS

recreation specialization, life satisfaction, psychological commitment, social support, marathon tourists

Introduction

> *"I run marathon as an excuse to travel to new places, meet new people and try out new food. Maybe I do not need an excuse to do all these things, but I think I may be hooked on running marathon now!"* (Mary, 2013).

With the rapid growth of marathon event in China, marathon event tourism is being studied in great demand in the leisure field (Wang et al., 2018). Statistical data showed that approximately 1,828 marathon events were held in 337 cities across China in 2019, attracting more than 7.13 million participants which represented an increase of 1.29 million participants compared with the number in 2018 (Chinese Athletica Association, 2020). Individuals were keen to travel away from the place of residence, and regarded harvesting marathon event as a key leisure pursuit (Sato et al., 2016). Previous studies found that marathon event brand and destination image were the significant predictors of runners' willingness to revisit (Hallmann and Breuer, 2010; Huang et al., 2015). Moreover, other factors such as destination attachment, event satisfaction, and travel distance can also influence individual's behavioral intention (Hallmann and Wicker, 2012; Filo et al., 2013).

Bryan (1977, 2000) developed a conceptual framework named "recreation specialization (RS)" to reflect various behaviors that people had showed during participating in leisure sport activities. Along with the progress of runner's leisure career, they usually exhibited a series of obvious characteristics related to RS. As mentioned in the study of Green and Jones (2005), sport tourism can provide serious participants with (i) a way to construct their leisure identity, (ii) a time and place to express them sharing the skill and knowledge of the activity, and (iii) a way to record their leisure career. Existing literature (Heo and Lee, 2010; Kim et al., 2011; Yang et al., 2019) also provided some evidence to support the role of RS on life satisfaction (LS). For example, Yang et al. (2019) confirmed that the core devotees of sport club reported experiencing higher degree of happiness, life satisfaction, and health when compared to those moderate ones. In a longitudinal study, scholars indicated that distance running events participation exerted a positive influence on participants' evaluations toward their lives (Sato et al., 2015).

While the previous study indicated that RS had a direct effect on individual's leisure satisfaction (Matsumoto et al., 2018; Kwon et al., 2021) and subjective wellbeing (Tian et al., 2020), few have examined the impact of RS as a multidimensional construct influencing marathon runners' LS, and little is known about the potential impact of the psychological commitment (PC) and social support (SS) on LS. Regarding the current dilemma, PC has been suggested as a key mediator in the relationship between leisure involvement and flow experience (Cheng et al., 2016). PC reflects individual's loyalty to the activities in which they involve (Pritchard et al., 1999). In other words, when people are seriously engaged in some leisure activities, they will gain a series of durable benefits which may contribute them to commit to those activities strongly (Stebbins, 2007; Cheng et al., 2016). In addition, SS (e.g., from family or friends) was seen as a key factor that can negotiate individual's leisure constraints (Brown et al., 2001). Usually, higher degree of SS may contribute to the role of RS on LS.

Therefore, the objectives of this study are triple fold. The first is to access how the behavior, cognition, and affect dimensions of RS influence runners' LS. The second is to examine the mediating effect of PC on the relationship between dimensions of RS and LS. The third is to test the moderating effect of SS on the relationship between dimensions of RS and LS.

Literature review and development of hypotheses

Recreation specialization and life satisfaction

The RS framework originated from Bryan (1977) was firstly used to explain recreational trout fishermen's attitudinal and behavioral differences. The essence of RS is that outdoor recreation participants usually progress along a continuum from general interest and low engagement to specialized interest and high engagement (Bryan, 2000). Since Bryan's original research, scholars had made great efforts on how to evaluate RS accurately. A three-dimension specialization model proposed by McIntyre and Pigram (1992) has been widely used, which included dimensions of behavior, cognition, and affect. The behavioral dimension measured prior experience with a specific activity and familiarity with a recreational setting (McIntyre and Pigram, 1992). The cognitive dimension referred to the level of self-assessed knowledge and skill that they have accumulated through significant personal efforts (Waight and Bath, 2014). The affective dimension was characterized by personal commitment and enduring involvement (Buchanan, 1985; McFarlane, 2004).

RS has been successfully applied to examine within-group differences among participants in outdoor leisure sport activities, including marathon (Park et al., 2018), cycling (Lamont and Jenkins, 2013; Shafer and Scott, 2013), camping (McIntyre and Pigram, 1992; McFarlane, 2004), canoe (Wellman and Smith, 1982), and hikers (Kim and Song, 2017). For example, using a latent profile analysis, hikers were divided into three subgroups: novice, affection-driven, and expert; they exhibited significant difference on their satisfaction and revisit intention (Song et al., 2018). In addition, previous studies also reported the role of RS as a dependent variable, an independent variable, or a mediating variable. For example, Cheung et al. (2017) verified that a direct and positive impact was found between RS and pro-environmental attitudes among birdwatchers in Hong Kong.

Although previous studies paid less attention to evaluate the role of RS on LS, they also provided some indirect and reliable evidence. A recent study confirmed a direct influence of RS on cycling participants' subjective wellbeing, a multidimensional construct consisted of LS, positive and negative experience (Tian et al., 2020). Enduring involvement, seen as affective dimension of RS by McIntyre and Pigram (1992), had a positive direct effect on LS among 10-mile running participants (Sato et al., 2018). Moreover, serious participants reported experiencing higher degree of LS and perceived health than the casual participants (Kim et al., 2011; Heo et al., 2013). In other words, as the level of behavior, cognition, and affect improved continuously in physical active leisure activities, people would be inclined to report a higher satisfaction with life.

Recreation specialization and psychological commitment

Commitment refers to a process through which an individual becomes dedicated to organize the patterns of their leisure behavior for expressing their needs (Buchanan, 1985). PC was defined as 'a tendency to be devoted to individual's activities participation despite alternative options are available' (Pritchard et al., 1999; Lee and Kyle, 2014). It was seen as an essential element for understanding why individuals choose to participate in a specific leisure activity, or revisit particular places (Backman and Crompton, 1991; Pritchard et al., 1999). Previous studies came to an agreement on dividing PC into four major dimensions: resistance to change, position involvement, volitional choice, and informational complexity (Pritchard et al., 1999; Iwasaki and Havitz, 2004).

As is known to us, individuals may experience complex and sequential psychological processes before becoming loyal participants (Iwasaki and Havitz, 1998).

A previous study indicated that individuals can experience some positive psychological states (e.g., wellbeing and contemplation) from the activities through conquering adversity, and accumulating knowledge, skill, or experience (Stebbins, 2018). In a qualitative research, scholar found that degree of RS acted as a predictor of event attendance, and individuals usually negotiated constraints (e.g., low confidence and no partner) in order to commit to event attendance (Lewis and Moital, 2013). Moreover, Cheng et al. (2016) confirmed that higher enduring involvement (e.g., attraction, self-expression, and centrality to lifestyle) can lead to a higher level of PC by employing a structural equation modeling. Kyle et al. (2004) also indicated that when tourists exhibited higher degree of leisure involvement, they would exhibit strong PC to the activity and place. Based on the statement above, this study deduces that when individuals continuously involved in marathon running, they will accumulate related experiences, identify their preference, and develop a commitment to the activity.

Psychological commitment and life satisfaction

Previous studies indicated that serious engagement in physically active activities often gained higher level of life satisfaction and health (Kim et al., 2011; Heo et al., 2013). Considering the essence of PC, "continuity" and "resistance to change," participants with higher degree of PC always acquired many durable benefits as the leisure career processed (Stebbins, 2007). In a longitudinal study, Sato et al. (2015) proposed that achievement and positive experience through running event engagement would be help for evaluating individual's life satisfaction. In other words, when individuals are strongly psychological commit to marathon events participation, they believe that it can contribute to own a higher LS.

Mediating role of psychological commitment

Previous studies paid great attention to examine the mediating role of individual's PC on the relationship between leisure involvement and behavioral loyalty (Iwasaki and Havitz, 2004; Kyle et al., 2004). For example, Kyle et al. (2004) confirmed that dimension of PC had an indirect effect between leisure involvement and behavioral loyalty among hikers along the Appalachian Trail. Bodet (2012) suggested that PC played a mediating role on the relationship between enduring involvement and loyalty in sport participation services. However, they ignored to explore the influence of PC between dimensions of RS and LS.

Existing literature suggested that physically active leisure can improve participants' quality of life through providing positive experiences, such as psychological involvement and flow experience (Sato et al., 2014; Cheng et al., 2016). As discussed in previous paragraphs, dimensions of RS (i.e., behavior, cognition, and affect) may have a positive impact on PC and LS (Kyle et al., 2004; Heo et al., 2013; Cheng et al., 2016; Sato et al., 2018); PC may positively associate with LS (Sato et al., 2015). Based on the statement above, this study suggested that runners will commit to engage in marathon event tourism as degree of their RS increases. They will conquer the difficulties and constraints, develop a higher PC, and gain more positive experience and durable outcome related to LS.

Social support as a moderator

SS generally refers to the 'process of interaction in relationship which improve, coping, esteem, belong, and competence through actual or perceived exchanges of physical of psychosocial resources' (Gottlieb, 2000). SS can contribute to individual's health outcome by modifying the effects of a stressful situation or impacting on health directly (House et al., 1988; Thoits, 1995). According to this opinion, SS can encourage individuals to maintain and initiate running activities by psychological variables such as self-efficacy. It also suggested that SS can provide important information or material resources which can increase degrees of participation. In addition, previous studies also suggested dimensions of RS may influence the evaluation of individual's LS (Kim et al., 2011; Heo et al., 2013). Considering these arguments above, the current study proposes that SS can strength the relationship between behavior, cognition, affect, and LS.

In this study, we aimed at examining the relationship between dimensions of RS, PC, LS, and SS among Chinese marathon tourists. Based on the ideas mentioned above, we proposed a conceptual hypotheses model that is shown in Figure 1.

> *H_1*: Marathon runners' behavior of RS has a positive influence on their LS.

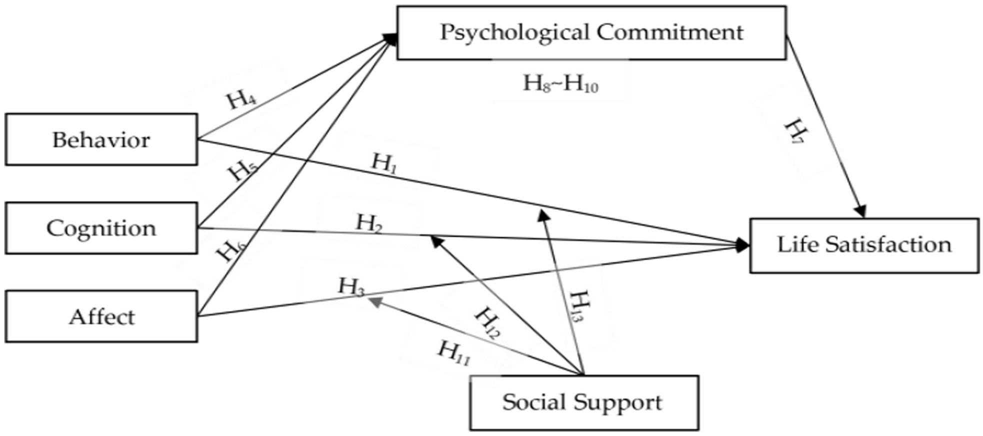

FIGURE 1
Proposed conceptual model.

H_2: Marathon runners' cognition of RS has a positive influence on their LS.

H_3: Marathon runners' affect of RS has a positive influence on their LS.

H_4: Marathon runners' behavior of RS has a positive influence on their PC.

H_5: Marathon runners' cognition of RS has a positive influence on their PC.

H_6: Marathon runners' affect of RS has a positive influence on their PC.

H_7: Marathon runners' PC has a positive influence on their LS.

H_8: Marathon runners' PC plays a mediating role between their behavior of RS and their LS.

H_9: Marathon runners' PC plays a mediating role between their cognition of RS and their LS.

H_{10}: Marathon runners' PC plays a mediating role between their affect of RS and their LS.

H_{11}: Marathon runners' SS plays a moderating role between their behavior of RS and their LS.

H_{12}: Marathon runners' SS plays a moderating role between their cognition of RS and their LS.

H_{13}: Marathon runners' SS plays a moderating role between their affect of RS and their LS.

Methodology

Measurements

RS was measured with 9 items modified from recent studies (Song et al., 2018; Tian et al., 2020); It was used to evaluate the degree of specialization for marathon running participants. The scale included three dimensions: behavior (3 items), cognition (2 items), and affect (4 items). The statement for affect was as follows: "If stopped running, I would lose touch with my friends." Both the behavioral and cognitive dimensions were rated on a 5-point Likert scale where "1" represents "novice" and "5" represents "expert." The affect dimension was assessed with a 5-point Likert scale where "1" represents "disagree strongly" and "5" represents "agree strongly."

Satisfaction With Life Scale (SWLS) which developed by Diener et al. (1985) was applied to measure the degree which a person positively evaluates the overall quality of his/her life. The Chinese-version SWLS was confirmed with good reliability and validity by Xiong and Xu (2009). The scale consists of five items with 7-point Likert scale where "1" represents "disagree strongly" and "7" represents "agree strongly." The statement for LS was as follows: "In most ways my life is close to my ideal."

Psychological Commitment Scale (PCS), modified from Pritchard et al. (1999) and Kyle et al. (2004), was used to measure the extent of commitment for marathon runners. A recent study reported that this scale appeared to exhibit satisfactory measurement qualities (Cheng et al., 2016). It included 10 items, covering four dimensions: resistance to change (3 items), position involvement (3 items), volitional choice (2 items), and information complexity (2 items). The statement for resistance to change was as follows: "My preference to participate in running will not willingly change." A 7-point Likert scale was used where "1" represents "disagree strongly" and "7" represents "agree strongly."

The Multidimensional Scale of Perceived Social Support (MSPSS), developed by Zimet et al. (1988), was applied to measure the respondent's social support. The MSPSS consisted of 12 items, reducing to three dimensions: significant other (4 items), friends (4 items), and family (4 items). The statement for significant other was as follows: "There is a special person in my life who cares about my feelings." The MSPSS was rated with a 7-point Likert scale where 1 represents "disagree strongly" and 7 represents "agree strongly."

According to the experiences of existing literature (Qiu et al., 2020; Tian et al., 2022), five demographic variables and a behavioral variable were introduced as covariate variables in the proposed model. They are gender, age, marital status, income, education, and the number of running event participation per year.

Procedures and date analysis

The data for this study were collected at the 2021 Xiamen International Marathon Event which was held on April 10 in Xiamen (a tourism city in southeast China). This event was recently certified as a world athletics elite platinum label event by International Athletics Federation, and has successfully attracted over 15,000 participants every year since 2015. Based on the size of the event, this study distributes the questionnaire randomly (i.e., every 20th person) to marathon runners near the finish area. The respondents were suggested to sign the informed consent before they start to fill out the questionnaire. A total of 393 questionnaires were collected through sharing a QR code from a web-based platform (i.e., Questionnaire Star), but 34 of the sample were excluded from the data analysis according to Gibson's (1998) definition of sport tourism, because they were not temporarily outside of their home communities. Finally, 359 questionnaires were used to examine all the research hypotheses.

SPSS 23.0 and JASP 0.16 were performed to analyze the data in this study. Parametric analyses, seen as the standard tools of psychological statistics (Norman & Anderson, 1961), were "robust" as judged from the observation that parametric and non-parametric analyses lead to similar results regarding statistical significance (Mircioiu and Atkinson, 2017). So parametric procedure was used to examine related data in this study. Specifically, the respondent profile, mean, and standard deviations were evaluated by descriptive analysis. Reliability of all the variables in this study was accessed using Cronbach's alpha (CA). The correlation of all the variables was evaluated by Pearson's correlation coefficient. Confirmatory Factor Analysis in JASP was performed to test the convergent validity and discriminant validity of all the subscales. Regression analysis was applied to examine hypothesis 1 to hypothesis 7. Process V 4.0 developed by Hayes et al. (2017) was used to decide hypothesis 8 to hypothesis 13.

Results

Respondent profile

Table 1 reports the profiles of the respondents. As a whole, most respondents were middle age, married, well-educated, and higher income.

Descriptive statistics

Before testing the research hypotheses, the reliability and validity of all constructs were examined by using JASP 0.16 in this study. As reported in Table 2, the internal consistency values ranged from 0.72 to 0.95, indicative of reliable consistency among the items in each subscale (Nunnally and Bernstein, 1994). Convergent validity reflects the extent to which a set of items possess the properties expected of the focal construct (Nunnally, 1967; Bagozzi and Yi, 2012). Three indicators, including factor loading (FL), composite reliability (CR), and average variance extracted (AVE), were used to evaluate the convergent validity of each construct. As shown in Table 2, the FLs for most items were high than 0.70 (i.e., 0.74 to 0.93), except for one item in the subscale of SS (FRI2 = 0.34). According to the suggestion of Hair et al. (2011), when an item's FL is below 0.70, it should be removed from the scale for increasing the CR. In this study, the reported CR values ranged from 0.71 to 0.92, and the AVE values ranged from 0.55 to 0.90. These indicators met the acceptable threshold of an AVE value higher than 0.50 (Barclay et al., 1995) and a CR value higher than 0.70 (Fornell and Larcker, 1981).

Table 3 presents the results of descriptive statistics and discriminant validity for each subscale. Affect had a higher mean score ($M = 3.76$, $SD = 0.84$) on the scale of RS, followed by cognition ($M = 3.60$, $SD = 0.91$); behavior had a lower mean score ($M = 2.72$, $SD = 0.96$). These results were consistent with the findings of a recent research (Tian et al., 2020). In terms of the PC scale, a higher mean score was found for volitional choice ($M = 5.62$, $SD = 1.04$), followed by resistance to change ($M = 5.53$, $SD = 1.07$) and position involvement ($M = 5.43$, $SD = 1.04$); information complexity had a lower mean score ($M = 5.33$,

TABLE 1 Respondent profile.

Variable	Characteristics	Frequency (n)	Percentage (%)
Gender	Male	251	69.9
	Female	108	30.1
Age	18–29	109	30.4
	30–44	115	32.0
	45–60	93	25.9
	61 and above	42	11.7
Marital status	Unmarried	82	22.8
	Married	251	69.9
	Divorced or widowed	26	7.2
Education	High school or below	21	5.8
	College or university	257	71.6
	Postgraduate	81	22.6
Income (/year)	US$3,000 and below	33	9.2
	US$3,001–US$7,500	64	17.8
	US$7,501–US$18,000	183	51.0
	US$18,000 and above	79	22.0
Event participant (/year)	1 to 2 times	65	18.1
	3 to 4 times	160	44.6
	5 to 6 times	107	29.8
	6 times above	27	7.5
Total		359	100

TABLE 2 FL, CA, AVE, and CR of each construct.

Constructs	Code	Items	FL	CA	AVE	CR
Specialization						
Behavior	BEH1	How long do you use for each run?	0.74	0.72	0.60	0.82
	BEH2	How many times do you run every week?	0.79			
	BEH3	How many years have you been running?	0.79			
Cognition	COG1	Knowledge of running	0.93	0.85	0.90	0.92
	COG2	Running skill	0.91			
Affection	AFF1	Running is very important to me	0.74	0.86	0.61	0.86
	AFF2	I find that much of my life is organized around running	0.83			
	AFF3	If stopped running, I would lose touch with my friends	0.80			
	AFF4	I would rather go running than do other activities	0.76			
Psychological commitment						
Resistance to change	REC1	My preference to participate in running will not willingly change	0.75	0.88	0.71	0.88
	REC2	It would be difficult to change my beliefs about running	0.87			
	REC3	Even if close friends recommended another pastime, I would not change my preference for running	0.90			
Position involvement	POI1	I prefer to participate in running because their image of the activity comes closest to reflecting my lifestyle	0.81	0.80	0.59	0.81
	POI2	When I participate in running it reflects the kind of person I am	0.78			
	POI3	I prefer to participate in running because provider's service makes me feel important	0.71			
Volitional choice	VOC1	My decision to participate in running was freely chosen from several alternatives	0.70	0.75	0.55	0.71
	VOC2	I am fully responsible for the decision to participate in running	0.78			
Information complexity	INC1	I consider myself to be an educated consumer regarding running	0.86	0.86	0.75	0.86
	INC2	I am knowledgeable about running	0.87			
Life Satisfaction	LS1	In most ways, my life is close to my ideal	0.85	0.90	0.67	0.91
	LS2	The conditions of my life are excellent	0.80			
	LS3	I am satisfied with my life	0.85			
	LS4	So far, I have gotten the important things I want in life	0.85			
	LS5	If I could live my life over, I would change almost nothing	0.72			
Social support				0.89	0.67	0.89
Significant other	SIO1	There is a special person who is around when I am in need	0.86			
	SIO2	There is a special person with whom I can share joys and sorrows	0.76			
	SIO3	I have a special person who is a real source of comfort to me	0.81			
	SIO4	There is a special person in my life who cares about my feelings	0.83			
Friends	FRI1	My friends really try to help me	0.75	0.84[b]	0.64[b]	0.84[b]
	FRI2[a]	I can count on my friends when things go wrong	0.34			
	FRI3	I have friends with whom I can share my joys and sorrows	0.86			
	FRI4	I can talk about my problems with my friends	0.79			
Family	FAM1	My family really tries to help me	0.81	0.84	0.65	0.88
	FAM2	I get the emotional help & support I need from my family	0.77			
	FAM3	I can talk about my problems with my family	0.86			
	FAM4	My family is willing to help me make decisions	0.79			

FL = factor loading; CA = Cronbach's alpha; AVE = average variance extracted; CR = composite reliability; All the factor loadings are significant at the 0.001 level of significance.
[a]Items have been excluded because the factor loadings were below 0.7.
[b]The values were computed after exclusion of the deleted items.

SD = 1.14). These results indicated that the respondents exhibited higher attitudinal loyalty for marathon running. On the scale of LS, the respondents also reported higher life satisfaction (*M* = 5.25, *SD* = 1.08), which indicated that the respondents were satisfied with the quality of their current life. As for the scale of SS, family had a higher mean score (*M* = 5.63, *SD* = 0.99), followed by friends (*M* = 5.52, *SD* = 1.07); significant other had a lower mean score (*M* = 5.45, *SD* = 1.16).

Discriminant validity reflects the degree to which a group of variables meant to measure a construct can differentiate the construct from others in the model. It can be examined by comparing the square root of the AVE and correlation between

TABLE 3 Descriptive statistics and discriminant validity.

Constructs	M	SD	BEH	COG	AFF	REC	POI	VOC	INC	SWL	SIO	FRI	FAM
BEH [a]	2.72	0.96	**0.77**	0.29	0.35	0.34	0.26	0.17	0.35	0.15	0.07	0.08	0.08
COG[a]	3.60	0.91		**0.91**	0.60	0.41	0.43	0.35	0.59	0.44	0.29	0.32	0.37
AFF[b]	3.76	0.84			**0.93**	0.55	0.57	0.40	0.55	0.41	0.33	0.36	0.38
REC[c]	5.53	1.07				**0.94**	0.83	0.69	0.75	0.56	0.47	0.50	0.56
POI[c]	5.43	1.04					**0.89**	0.73	0.78	0.61	0.55	0.58	0.59
VOC[c]	5.62	1.04						**0.75**	0.59	0.57	0.51	0.55	0.58
INC[c]	5.33	1.14							**0.93**	0.62	0.47	0.48	0.52
LS[b]	5.25	1.08								**0.95**	0.59	0.60	0.61
SIO[c]	5.45	1.16									**0.94**	0.82	0.70
FRI[c]	5.52	1.07										**0.86**	0.77
FAM[c]	5.63	0.99											**0.92**

The correlation coefficients are shown in the upper diagonals. The square roots of the AVE values are shown in boldface type in the diagonal.
[a]Rated on a 5-point scale from 1 (novice) to 5 (expert).
[b]Rated on a 5-point scale from 1 (disagree strongly) to 5 (agree strongly).
[c]Rated on a 7-point scale from 1 (disagree strongly) to 7 (agree strongly).

the constructs (Fornell and Larcker, 1981). As shown in Table 3, the square roots of the AVE of all the subscales were high than the correlation coefficient of other constructs (See the diagonal versus non-diagonal elements), which suggested all the constructs showed acceptable discriminant validity.

In addition, all constructs used in this study had significantly positive correlations with each other ranging from 0.07 to 0.83, $p < 0.01$.

Hypothesis testing results

The multiple regression was performed to examine the hypothesis 1 to hypothesis 7. The statistical results confirmed that behavior ($\beta = 0.15$, $p < 0.01$), cognition ($\beta = 0.35$, $p < 0.001$), affect ($\beta = 0.28$, $p < 0.001$), and PC ($\beta = 0.59$, $p < 0.001$) have positive and significant effects on LS. Thus, hypotheses H1, H2, H3, and H7 are supported. Similarly, the results confirmed that behavior ($\beta = 0.22$, $p < 0.001$), cognition ($\beta = 0.38$, $p < 0.001$), and affect ($\beta = 0.43$, $p < 0.001$) have positive and significant impacts on PC. These findings support hypotheses H_4 to H_6.

The mediating role of psychological commitment

As Table 4 illustrates, the indirect effects were estimated and the 95% confidence intervals were calculated. Specifically, the mediating role of PC on the relationship between behavior, cognition, affect, and LS was significant as zero was not included in any of the confidence intervals. That is (a*b = 0.09, LB = 0.05, UB = 0.14), (a*b = 0.14, LB = 0.08, UB = 0.20), and (a*b = 0.20, LB = 0.11, UB = 0.29), respectively. Following the suggestion of Wen and Ye (2014), it was confirmed that PC fully mediated the relationship between behavior, cognition, and LS. However, PC partially mediated only the relationship between affect and LS. Therefore, these findings indicate that PC has a mediating effect between behavior, cognition, affect, and LS, confirming hypotheses H_8 to H_{10}.

The moderate role of social support

The moderation role of SS on the relationship between dimensions of RS and LS was tested as shown in Table 5. For analysis, three interaction variables were produced, including SS × behavior, SS × cognition, and SS × affect. According to the results, the effect of SS × affect on LS was significant ($\beta = 0.10$, $p < 0.05$). However, the effect of SS × behavior ($\beta = 0.03$, $p > 0.05$) and SS × cognition ($\beta = 0.06$, $p > 0.05$) on LS was not significant. In other words, SS can significantly promote the relationship between affect and LS. While SS did not provide any significant impact for the role of behavior and cognition on LS.

Discussion

The present study extends existing literature on runner's RS toward marathon event tourism in three main ways. First, we sought to clarify how RS dimension (i.e., behavior, cognition, and affect) and runners' PC are related. Second, this study examined the mediating effect of PC on the relationship between RS dimensions and LS. Third, the current study investigated the moderating role of SS between RS dimensions and LS. A proposed conceptual model was designed to examine the relationship between dimensions of RS, PC, LS, and SS among marathon event tourists in China. The standardized estimate results for this study supported 11 out of the 13 hypotheses, with H_{11} and H_{12} as the exception.

As shown in Table 6, this study fills the gap in the existing literature by revealing a significant and positive influence of runners' RS dimensions on their LS. The findings were consistent with previous contributions that have shown a link

TABLE 4 Mediating effect of PC.

No.	Hypothesis	IPC	BootSE	95% CI		DPC	Decision
				Lower	Upper		
H_8	Behavior → PC → SWL	0.09	0.03	0.05	0.14	0.08	FMS
H_9	Cognition → PC → SWL	0.14	0.03	0.08	0.20	0.21	FMS
H_{10}	Affect → PC → SWL	0.20	0.04	0.11	0.29	0.08*	PMS

IPC = indirect path coefficient; DPC = direct path coefficient; FMS = full mediation supported; PMS = partial mediation supported.

TABLE 5 Moderating effect of SS.

No.	Hypothesis	β	p	95% CI		Decision
				Lower	Upper	
H_{11}	SS × Behavior → LS	0.03	0.48	−0.05	0.11	Not supported
H_{12}	SS × Cognition → LS	0.06	0.16	−0.02	0.14	Not supported
H_{13}	SS× Affect → LS	0.10	0.03	0.01	0.20	Supported

TABLE 6 Main regression results in the proposed research model.

No.	Hypothesis	β	t-value	Decision
H_1	Behavior → LS	0.15**	2.93	Supported
H_2	Cognition → LS	0.35***	7.66	Supported
H_3	Affect → LS	0.28***	5.68	Supported
H_4	Behavior → PC	0.22***	4.90	Supported
H_5	Cognition → PC	0.38***	8.84	Supported
H_6	Affect → PC	0.43***	10.09	Supported
H_7	PC → LS	0.59***	12.64	Supported

** $p < 0.01$; *** $p < 0.001$.

between behavior, cognition, affect dimension, and runners' LS (Heo et al., 2013; Sato et al., 2018). Activity theory claimed that the amount or frequency of activity participation and the level of attachment related to an activity could impact a person's LS (Lemon et al., 1972). This research also extended to understand the antecedent factors of LS. As mentioned in previous studies, when individuals exhibited a serious level of behavioral engagement, knowledge acquirement, and emotional attachment, their LS always increased correspondingly (Kim et al., 2011; Heo et al., 2013).

According to study results, RS dimensions were significantly and positively related to runners' PC. The results enrich existing research of Kyle et al. (2004), Cheng et al. (2016), and Ridinger et al. (2012), which confirmed that tourists showed strong PC to their pursuits when they presented a high level of leisure involvement. Recent suggested that individual's self-discipline behavior and curiosity on activity can make them acquire a series of physical, psychological, and social benefits, which may indirectly strengthen their degree of PC (Stebbins, 2018). Moreover, the findings of this study provided some supports to Sato et al. (2015) and Stebbins (2007) finding that positive experience was positively associated with people's LS.

Study results revealed that runners' PC can play a mediating effect between RS dimensions and LS. Previous research have confirmed the mediating role of PC between leisure involvement and flow experience, and consumer loyalty (Iwasaki and Havitz, 2004; Bodet, 2012; Cheng et al., 2016). By developing a structural modeling, Lee and Scott (2006) suggested that as individual became increasing specialized, the benefits they obtained far outweighed any costs they might experience along the way. In addition, high quality of life is always rooted in a capacity to search deep satisfaction and fulfillment through experiencing with serious leisure to eventually carve out an optimal leisure lifestyle (Stebbins, 2007). Therefore, the findings in this study contribute to understand the connection between RS dimensions and LS, especially the indirect effect of PC on the relationship between behavior, cognition and LS.

Extending to previous study (Ricciardo et al., 2006), this study demonstrated that affect dimension interacted with SS when it predicted individual's LS. Existing literature confirmed that positive social influences had a positive influence on individual's negotiation efforts among the process they become specialized (Kim et al., 2019), they played a key role in achieving diverse durable benefits and developing unique leisure identities (Lyu and Oh, 2015). Therefore, higher social support can strengthen the positive role of affect dimension on runner's LS. However, SS did not significantly moderate the role of behavior and cognition on runners' LS. In other words, individuals may use other negotiation strategies related to intrapersonal and structural constraints for pursuing a satisfied life when they processed toward a higher level of specialization (Park et al., 2017).

Although this study provides valuable insight into the relationship between dimension of RS, PC, LS, and SS in a leisure background, there are some limitations as follows. First, the findings in this study were confirmed under the background of COVID-19 pandemic, which has impacted all aspects of individual's everyday life, especially the experience of event participant and evaluation on their life. Hence, the results should be re-examined after conquering the COVID-19 pandemic. Second, while the proposed conceptual model has been carefully designed, this study may still ignore variables such as self-efficacy, leisure motivation, and leisure constraints. It should explore the influence of these variables on the theoretical framework in the future. Third, this study collected data from a random convenience sample of marathon runners in Xiamen Marathon Event. Future study should recruit the respondents from a wider geographic area and other types of activities.

Conclusion

Physically active leisure plays an important role in promoting individual's LS (Sato et al., 2015, 2018). Study results contributed to existing literature by confirming the positive influence of behavior, cognition, affect, PC on runners' LS, and the moderating role of SS with affect on runners' LS. Considering the normalization of the COVID-19 pandemic, these results could open a new door to the leisure and recreation manager, marathon event organizer, and marathon participants for weaving a satisfied everyday life.

From a theoretical perspective, the findings support the positive impact of physically active leisure participation on experiencing higher level of LS. These results also extended the existing literature (Kim et al., 2011; Sato et al., 2018) by examining the mediating effect of PC, and the moderating role of SS. In addition, they also contribute to understand the predictors and influential paths of LS. From a practical perspective, individuals can experience a high degree of LS from being specially engaged in physically active leisure. In terms of individuals, they should make significant personal effort to conquer adversity, accumulate knowledge and skill, and form a long-lasting leisure career. For providers of leisure sport service, improving the quality of events, popularizing the sport skill and knowledge, and encouraging social group culture may be the best way for improving individual's LS.

Data availability statement

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

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the patients/ participants or patients/participants legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

YQ: methodology, project administration, and funding acquisition. HT: formal analysis, writing—original draft preparation, and writing—review and editing. WZ: investigation. HT and WZ: data curation. All authors contributed to the article and approved the submitted version.

Funding

This research was supported by the Starting Research fund from Shaoxing University (No. 20216011), the Hengyi foundation of Zhejiang University, and national social science funding in China (No. 16BTY077).

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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frontiers | Frontiers in Big Data

TYPE Original Research
PUBLISHED 20 July 2023
DOI 10.3389/fdata.2023.921355

Too much information is no information: how machine learning and feature selection could help in understanding the motor control of pointing

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RECEIVED 15 April 2022
ACCEPTED 16 June 2023
PUBLISHED 20 July 2023

CITATION
Thomas E, Ali FB, Tolambiya A, Chambellant F and Gaveau J (2023) Too much information is no information: how machine learning and feature selection could help in understanding the motor control of pointing.
Front. Big Data 6:921355.
doi: 10.3389/fdata.2023.921355

The aim of this study was to develop the use of Machine Learning techniques as a means of multivariate analysis in studies of motor control. These studies generate a huge amount of data, the analysis of which continues to be largely univariate. We propose the use of machine learning classification and feature selection as a means of uncovering feature *combinations* that are altered between conditions. High dimensional electromyogram (EMG) vectors were generated as several arm and trunk muscles were recorded while subjects pointed at various angles above and below the gravity neutral horizontal plane. We used Linear Discriminant Analysis (LDA) to carry out binary classifications between the EMG vectors for pointing at a particular angle, vs. pointing at the gravity neutral direction. Classification success provided a composite index of muscular adjustments for various task constraints—in this case, pointing angles. In order to find the combination of features that were significantly altered between task conditions, we conducted a post classification feature selection i.e., investigated which combination of features had allowed for the classification. Feature selection was done by comparing the representations of each category created by LDA for the classification. In other words computing the difference between the representations of each class. We propose that this approach will help with comparing high dimensional EMG patterns in two ways; (i) quantifying the effects of the entire pattern rather than using single arbitrarily defined variables and (ii) identifying the parts of the patterns that convey the most information regarding the investigated effects.

KEYWORDS

motor control, machine learning, feature selection, pointing, explainable machine learning

1. Introduction

Movement takes place through the contractions of several muscles which then cause the displacement of several body segments. Much pain and energy therefore goes into the simultaneous collection of the variables connected with motor control studies. Curiously despite the energy invested in the synchronization of the data collection and the big data tables created by such experiments, the analysis of it largely takes place in a univariate manner. In this study we propose the use of Machine Learning classification as a technique able to provide insights concerning global features of the voluminous datasets created from motor control studies. The use of these techniques with movement data is not new. However, it has been principally in the realm of application, largely unconcerned with questions concerning underlying mechanisms (Phinyomark and Scheme, 2018; Côté-Allard et al., 2019; Parajuli et al., 2019; Labarrière et al., 2021; Xiong et al., 2021). Compared to this, there are few studies using Machine Learning dedicated to the purpose of understanding the mechanisms underlying movement. There are many advantages to be gained from exploring this technique for understanding motor control. First, Machine Learning allows for the combination of variables in analyses hence providing the means for a global view. This is similar to the manner in which humans make decisions—weighing the input from a combination of features before arriving at a conclusion (Drugowitsch et al., 2014; Mercier and Cappe, 2020). Second, linear or nonlinear feature combinations of variables could allow for significant differences in cases where they would not individually. Thirdly, with a technique of classification and then feature analysis, we are using an approach that is more in keeping with the current spirit of "big data". Rather than imposing previously held views concerning which variables are important, we allow this information to emerge from an understanding of which variable combination is important for classification. This process of identifying the features which are important for classification is an important field in Machine Learning called feature selection (Guyon and Elisseef, 2003; Saeys et al., 2007; Hira and Gillies, 2015; Jović et al., 2015; Venkatesh and Anuradha, 2019).

The motor control task studied in this paper was one of pointing in different directions. Subjects pointed in the gravity neutral horizontal dimension of 90° and then at 180° (vertically downwards), 135°, 45° and 0° (vertically upwards) (Figure 1). These four directions entailed gravity constraints of varying degrees. Since the electromyographic activity (EMG) of nine muscles were recorded at high frequency (1,000 Hz) during pointing, each movement was associated with several high dimensional vectors for each subject. Although they have much to offer in the way of understanding motor control, EMG signals are not used as often as kinematic data in part due to their high complexity and intra and inter subject variability (Latash, 2012; Hagen and Valero-Cuevas, 2017). The experimental results describing the kinematic aspects of this current study have been published (Gaveau et al., 2016).

Machine learning was used to analyse the data as it would provide us with a means of conducting a simultaneous analysis of all the recorded EMGs. The task was approached as a binary discrimination task with each case being the classification of EMGs in the gravity neutral direction of 90° compared to pointing at 180°, 135°, 45°, or 0°. Importance was given to the use of Linear Discriminant Analysis (LDA) as the algorithm for classification. In LDA, the means and variance of each group are used to construct models of each group which are multivariate Gaussians. The probability of a data point belonging to one class or the other is then computed with the help of the Bayes factor (Grimm and Yarnold, 2006; Johnson and Wichern, 2007; Izenman, 2013). This is a relatively old algorithm and several previous studies including some of our own have shown that more recent techniques like the kernel methods (Support Vector Machines belong to this group of methods) or random forest trees provide better classification (Statnikov et al., 2008; Nair et al., 2010; Heung et al., 2016; Han et al., 2017; Uddin et al., 2019). We nevertheless chose to work with this technique due to its ease of application especially with regards to feature selection. We also hope that its conceptual connection with classical univariate statistics would also encourage the greater use of machine learning in the basic science studies of motor control.

Once the classification has been performed we proceeded to identify the feature combination which had allowed for discrimination. This process of feature selection in the field of engineering is largely for the purpose of reducing the size of datasets and hence speeding up classification. These efforts therefore concentrate on picking the *minimum* number of features necessary for classification. In contrast, the application of such techniques to the basic sciences, would require an identification of several of the features/feature combinations which have been altered. Standard features selection techniques can be grouped into the categories of filter, wrapper and embedded techniques. Review articles which explain the central philosophies of each of these techniques can be found in several previous publications (Guyon and Elisseef, 2003; Saeys et al., 2007; Hira and Gillies, 2015; Jović et al., 2015; Remeseiro and Bolon-Canedo, 2019; Venkatesh and Anuradha, 2019). Filter methods are usually pre machine learning methods which first assign a statistical score to each feature. They are generally used as a pre-processing step and selection of features is independent of any machine learning algorithms. The features are then ranked according to these scores and the features which are within a cutoff threshold are kept. These methods are often univariate. Some examples are the chi squared test and correlation coefficient score. Wrapper methods are based on the results obtained from machine learning algorithms. Through recursive processes, the method uses various search methods to assemble feature combinations which are then tested using the classification algorithm. Putting together the feature combinations can range from greedy algorithms like sequential forward selection or more optimized search methods like randomized hill climbing. In embedded techniques, the search for the optimal feature combination for classification is done as the machine learning algorithm is being constructed. Regularization methods are embedded feature selection methods. Such methods give a weight to each feature that the learning algorithm optimizes, so that the unimportant features have a close to zero weight and are eliminated from the algorithm calculations. Examples of such algorithms are LASSO (Least Absolute Shrinkage and Selection Operator) (Tibshirani, 1996) and ridge regression (Hoerl and Kennard, 1970). The feature selection method used in this study would fall under the embedded method category. Classification begins with a full feature vector. The differences between the models of each class created by LDA is then used to find the group of important features. We chose this method because it was in keeping with intentions of finding feature combinations which are altered between task conditions and to avoid making pre-suppositions concerning altered features. A successful categorization indicates the presence of information

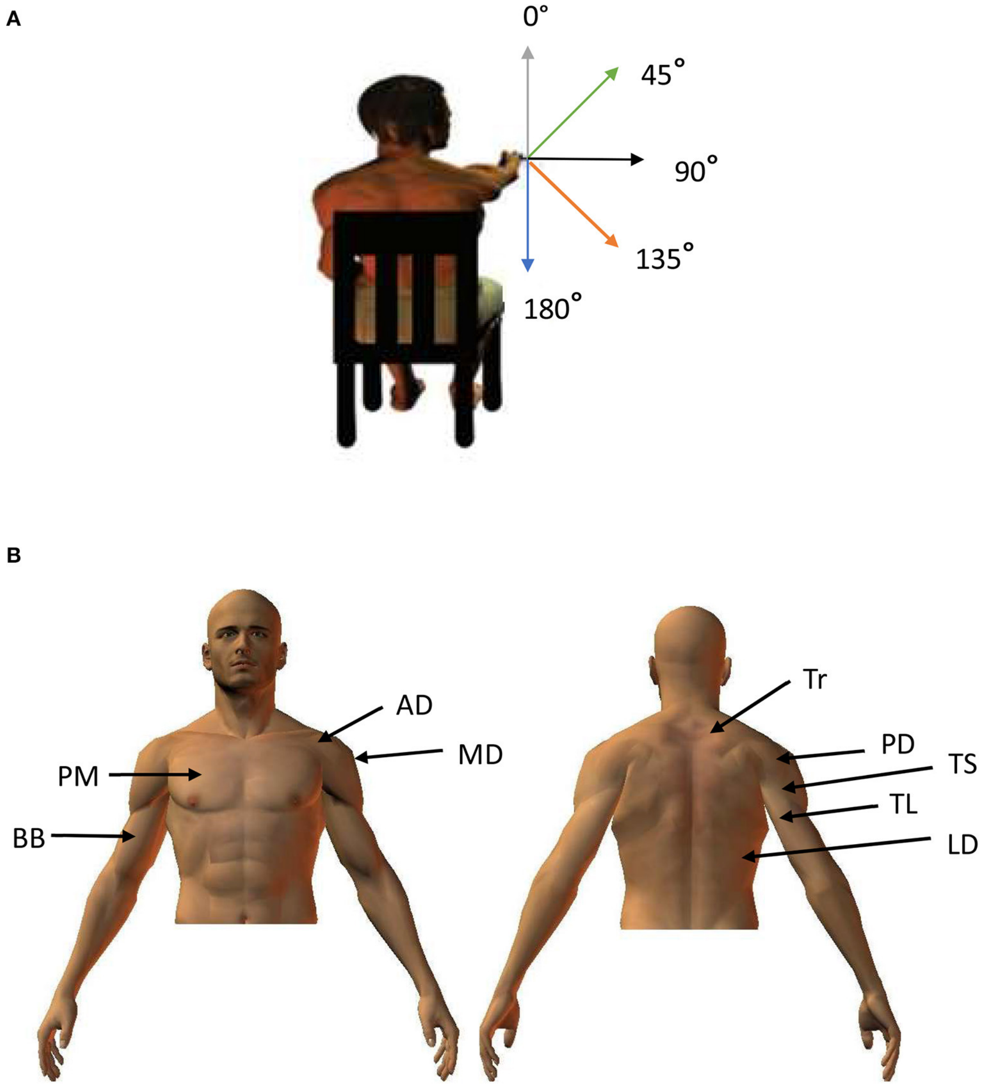

FIGURE 1
(A) Participants were seated with a hand held horizontally in front of them. They were then asked to point to targets placed at 180°, 135°, 45°, and 0° **(B)** Approximate positions of recorded muscles.

which is discriminatory between two groups. The representation of each category can then be analyzed for finding the most relevant features to classification.

There is a good deal of information available concerning EMG activation patterns during pointing in different directions. These studies have helped to tease out the portion of muscular control which is involved in postural aspects of the movement from the aspects which are specifically related to directional tuning. The former, tonic EMGs, do not scale with task constraints such as speed while the latter, phasic EMGs, do so. These studies have also identified muscular alterations for pointing direction (Flanders, 1991; Flanders and Herrmann, 1992; Buneo et al., 1994, 2008; Flanders et al., 1996). Work by Gaveau et al. has shown how differences in the kinematics and muscular activity of downward and upward pointing can be related to the minimization of effort (Gaveau et al., 2016, 2021; Poirier et al., 2022a). The group also showed how this minimization is altered with age (Poirier et al., 2022b).

Almost all the studies in motor control are univariate, following the traditional pattern of picking variables based on pre-conceived notions and comparing them using traditional statistics. An important exception to this has been the work using principle component techniques and its variants. This technique has also provided a composite image of muscular alterations during pointing by finding components which capture most of the variance in the data. Data dimensionality reduction in this technique has focused on finding a few synergies that can then be scaled to reproduce EMG patterns for several constraints (d'Avella et al., 2010, 2011; Delis et al., 2018). The main difference between this sort of technique and the Machine Learning Classification and feature selection techniques, is the nature of the focus on the data. While the former is primarily concerned with correlations and global similarities, the latter is concerned with global differences. Here we will illustrate the novelty of this approach by using LDA to ask the following question - What are the muscular differences when pointing at a particular angle compared to pointing in a gravity neutral direction?

The aim of this study is to investigate how LDA classification can be used to pick out the muscle combinations and temporal segments of EMG data that are most pertinent to changing pointing direction. Since the technique is able to provide composite indices of performance such as classification accuracy, or distance between models, we also aim to use these as a guide on global trends in muscular modifications for changing pointing directions.

2. Method

The aim of this project is to use Machine Learning in order to understand how muscle organization changes as a function of pointing direction. In order to do so, we will investigate if the class representations created during Machine Learning can be exploited for finding the features/muscles that are adapted for pointing direction. To this end, we will:

- Describe how the kinematic and EMG data were collected. Markers placed on the arm recorded kinematic data and hence allowed the researchers to verify the direction of arm movement. This section will only be brief as a detailed description of the kinematic aspects of the current study have already been published (Gaveau et al., 2016).
- Describe the pre-processing of the EMG data
- Describe how the data was organized as input for the machine learning classification
- Provide a brief description of the LDA algorithm
- Describe the technique of feature selection through the comparison of models created of each class by LDA.

2.1. Data acquisition

The input dataset used for the current investigation came from a previous study (Gaveau et al., 2016) which had been approved by the regional ethics committee of Burgundy. Data collection was carried out in keeping with regional and international norms (Declaration of Helsinki, 1964). It consisted of kinematics values and EMG signals recorded from 11 right handed healthy participants of mean age 24 ± 3.2 years (9 female, 2 male) who had given their written consent for the study. Right handed preference was evaluated by the Edinburg test (individual scores >0.86; Oldfield, 1971).

The participants pointed in different directions from a seated position. They were seated with a hand held horizontally in front of them. They were then asked to point to targets placed at 180°, 135°, 45°, and 0°as shown in Figure 1. The order of pointing in different directions was randomized. There were nine trials for each angle. The movements of the arm were followed through the use of kinematic markers placed on the shoulders, arm and hand of the subjects. For our purpose, we were only interested in the hand marker placed on the first metacarpo-phalageal joint. The trajectory of the marker was recorded using an optoelectronic system (Smart BTS Italy) with 4 cameras sampling at 120 Hz. The X, Y, and Z coordinates of the markers throughout the pointing movement were stored to identify the direction of pointing. Movement onset and offset were defined as the time at which hand tangential velocity went above or fell below 5% of maximum hand velocity.

The EMG data was obtained from surface electrodes placed on 9 muscles using the Aurion, Zerowire EMG at a sampling frequency of 1000 Hz. The muscles recorded from were the anterior deltoid (AD), posterior deltoid (PD), medial deltoid (MD), pectoralis major (PM), latissimus dorsi (LD), trapezius (Tr), biceps brachii (BB), long triceps (TL) and short triceps (TS). We applied the following standard procedures to the EMG data. They were band pass filtered with a bandwidth from 20 to 300 Hz, using the "butter" and "filtfilt" functions in Matlab. Before integrating the signal using a sliding window of 5 ms, each EMG signal was cut off 200 ms before movement onset and at movement offset. Finally, EMG data were filtered one more time to obtain smooth patterns (low-pass 5 Hz). Interpolation was used to place all the collected time series on a common time base. i.e., duration was normalized.

2.2. Classification

All the classifications carried out in this study were binary classifications. Muscular activity for pointing at 90°was chosen as a reference direction. This was done because horizontal arm movements are gravity neutral whereas movements in the other directions move the arm in or against the direction of gravity. So the binary classifications carried out were 90°vs 180°, 135°, 45°, and 0°. A succinct description of the steps taken for the LDA analysis are the following

1. For each subject, normalize the EMG amplitudes for each muscle so that the maximum amplitude is 1 and the minimum is −1.
2. Link the EMGs for all the muscles of each trial to create input vectors
3. Divide the subjects into five folds
4. Keep four folds for training and the remainder for testing
5. Using the Matlab LDA algorithm, create representations of each class only using the four training folds.
6. Verify goodness of this representation by testing classification using the remaining test fold.
7. To obtain the LDA_{diff} vector subtract the representations of each category
8. Portions of the LDA_{diff} vector which have a high amplitude indicate importance in classification. A cutoff margin can therefore be progressively lowered to pick out the most important portions of the LDA_{diff} vector (a schematic representation of the feature selection process can be seen in Figure 2).
9. Repeat the process with the next training and testing fold.

More details of each step are provided in the sections below.

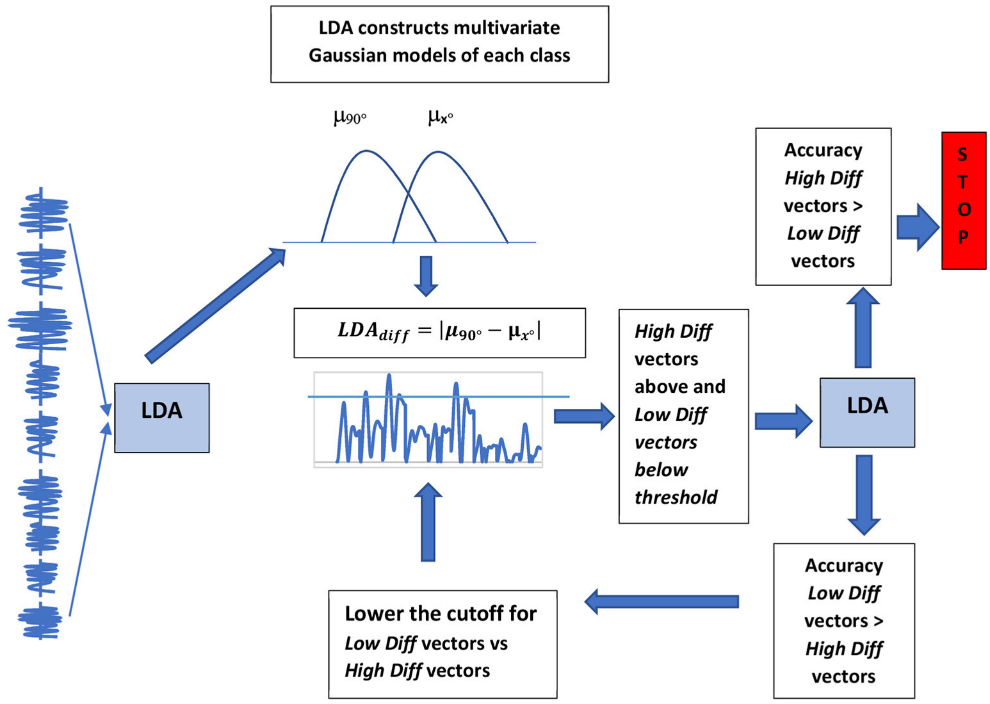

FIGURE 2
Flow diagram describing procedure for picking out portions of the input vector which are the most important for classification.

2.2.1. Input data organization

Input data was organized as was done in many of our previous studies (Nair et al., 2010; Tolambiya et al., 2011, 2012; Laroche et al., 2014). The input vectors for classification algorithm were created through the concatenation of the kinematic or EMG time series for each trial. As explained in the data acquisition section above, the time series for each variable was a vector of 1000 elements. So for example, taking the case of the kinematic data, the input vector for each trial was 3000 elements long as we concatenated the X, Y, and Z time series for a trial. Since a subject pointed to each direction 9 times, the total kinematic matrix for each subject was 9 × 3000 for one angle. The same was done for the EMGs. Since there were nine muscles, the EMG vector for each trial was composed of 9000 elements and the EMG matrix for one direction was 9 × 9000 for each subject.

It is to be noted that throughout the study we kept the entire time series of any sensor rather than using condensed features such as averages or frequencies. We also did not use features extraction techniques like PCAs to reduce dimensionality. This was done so as to facilitate the task of identifying the features which are important for the classification, not only in terms of muscles but also in terms of *when* the important muscular modifications took place.

The study was done using 5 fold cross validation. Due to the awkward number of participants, four of the folds had two subjects while the final fold had 3. In accordance with cross validation protocol, every trial was sometimes used as training data and other times as testing data. However, there were no classification tests in which data played both training and testing roles at the same time.

Accuracy was computed as the mean accuracy over all test sets. As is the case for most studies on Machine Learning the data was normalized so as to give equal importance to each muscle. For each individual and each muscle, the maximum EMG amplitude was given the value 1 and a value of −1 was assigned to the minimum. The normalization was done over all trials and separately for each class of binary classification. Note that this form of normalization allows each muscle to have equal importance in classification. It also preserves differences in EMG amplitude when pointing in different directions.

2.2.2. Linear discriminant analysis for classification and feature selection

Classification and feature selection was done using Linear Discriminant Analysis (LDA) (Grimm and Yarnold, 2006; Johnson and Wichern, 2007; Izenman, 2013). As already mentioned in the methods section, all classification was binary. If we have a p dimensional vector x, the class k to which it belongs can be determined by computing the posterior probability that it belongs to a class Y = k by using Bayes rule. In this case x is an EMG vector and Y would be either 90° or the other angle with which we are conducting the binary classification. The conditional probabilities that x belongs to $k = 90^\circ$ or $k =$ another angle are computed and compared using Bayes factor (equation 1). The conditional probability that given the EMG vector x, pointing would have been done in the direction k is given by the equation

$$\Pr\left(Y = k \middle| X = x\right) = \frac{f_k(x)\pi_k}{\sum_{l=1}^{k} f_l(x)\pi_l} \qquad (1)$$

Where $f_k(x)$ is the density function of x. We can think of it as the model that LDA is using to represent each class k. It is the multivariate Gaussian of the data in each class.

$$f_k(x) = \frac{1}{2\pi^{\frac{p}{2}} |\Sigma|^{\frac{1}{2}}} e^{\frac{-(x-\mu_k)^T}{2} \sum_k^{-1} (x-\mu_k)} \quad (2)$$

where μ_k the mean of the class and Σ is the $p \times p$ covariance matrix of x.

The variable π_k is the prior probability for class k. It is computed as the proportion of samples belonging to class k

$$\pi_k = \frac{Number\ of\ samples\ in\ class\ k}{Total\ number\ of\ samples} \quad (3)$$

In our case, as there is an equal number of samples for each class, this factor was always 0.5. The conditional probability for x would have to be computed for 90° as well as the second angle being considered and x would belong to the class Y = k with the highest posterior probability

$$Y = \arg\max_T \ k \Pr\left(Y = k \middle| X = x\right) \quad (4)$$

Feature selection was done by computing the variable LDA_{diff}, obtained by comparing the models of each class created by LDA. This was the difference between the mean vector μ of each category which had been used by LDA to model each group. A schematic diagram of this process can be seen in Figure 2. So if we were comparing the EMGs for pointing in two directions *k1 and k2*

$$LDA_{diff} = |\mu_{k1} - \mu_{k2}| \quad (5)$$

The cutoff threshold for finding the *High Diff* and *Low Diff* vectors from LDA_{diff} was found in an iterative manner. It started at a high threshold value and was lowered step by step until the classification using the features above threshold was higher than what was obtained using the features below. Vectors that contain features above the cutoff threshold were called *High Diff* vectors, and those below, *Low Diff* vectors. Muscles which contained parts of the *High Diff* or *Low Diff* vectors were called *High Diff* or *Low Diff muscles*. The capacity of these EMG vectors to predict task constraints is reported in the Results section.

To obtain an idea of the composite difference between classes, we also computed another variable which we called the $LDA_{distance}$. It was the sum of all the values in LDA_{diff}.

$$LDA_{distance} = \sum_{i=1}^{p} |\mu_{k1} - \mu_{k2}|_i \quad (6)$$

The LDA algorithm was implemented using Matlab (The MathWorks, Inc., Natick, Massachusetts, United States).

2.2.3. Statistics

In keeping with the categorical nature of classification, the statistics for the study were primarily done using the χ^2 test i.e., by comparing the number of wrong vs. right answers. When comparing the classification results for two different angles, we constructed contingency tables for the number of right vs. wrong answers for each angle (Howell, 1992; Hinton, 1995). In the case of multiple comparisons, where we compared the classification accuracies at several angles, we applied the Bonferroni correction (Dunn, 1961; Goeman and Solari, 2014). Since this involve four pointing directions, results were significant if $p < 0.0125$. As Figure 3B did not involve accuracies but a continuous variable, we used the Friedmann test followed by a planned comparison of the $LDA_{distance}$ for the classification at 180° vs. 0°. The result was taken to be significant if $p < 0.05$.

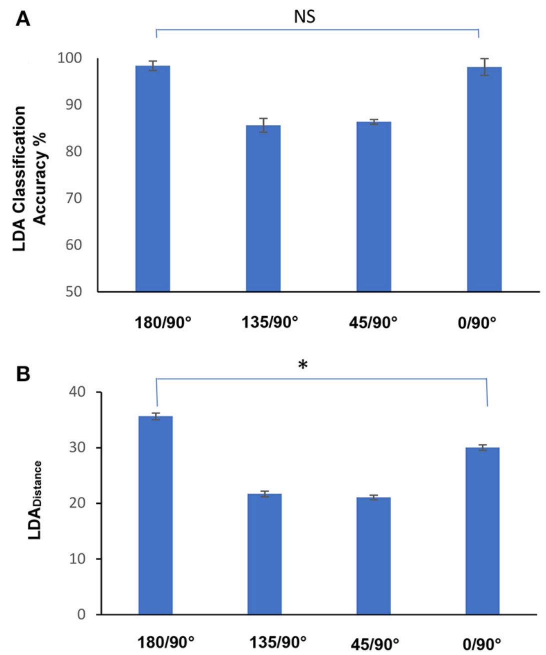

FIGURE 3
(A) Classification accuracies from binary classifications between EMGs from pointing at 90° vs. 180°, 135°, 45°, and 0°. Of note was the lack of significant differences between pointing at 180° and 0° ($p > 0.05$, χ^2 test). **(B)** The values of $LDA_{distance}$ obtained from the same classifications which were performed for **(A)**. While the classifications accuracies are similar for downward and upward pointing directions, the $LDA_{distance}$ variable shows that when compared to pointing in the gravity free horizontal dimension, EMG adjustments were greater when pointing downwards at 180° than when pointing upwards at 0° ($p < 0,05$, Friedmann, followed by Wilcoxon planned comparison). All values represented in the figure are the means ± standard error of the mean.

3. Results

In this section we will present the results from analyzing the kinematics and EMG activities for different pointing directions. In each case, we will start out with the classification results of a full vector with all the features before comparing the models of each category to pick out the combination of features that are the most different between two task conditions, in other words, computing the LDA_{diff} vector. This will then be followed by a comparison of the classification with the *High Diff* time series compared to classification with the *Low Diff* time series, the time series being either a muscle EMG or a kinematic time series. The investigation

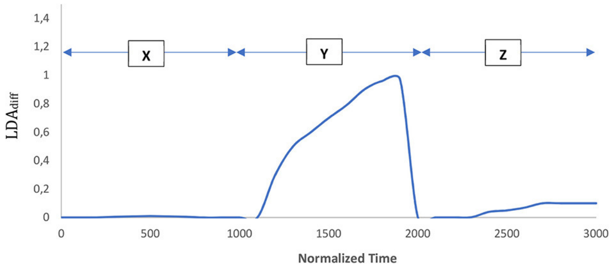

FIGURE 4
An example of a difference vector obtained by subtracting representations of each category following binary clasification of XYZ coordinates from kinematic markers from pointing toward 180° and 0°.

TABLE 1 Comparison of classification accuracies using the High Diff versus Low Diff kinematic time series.

Classifier	LDA	SVM	LVQ
High Diff Vector	100	100	100
Low Diff Vector	76.7	81.19	74

All values in the table are mean percentages.

of this technique will first start with the easier example of automatic classification using the kinematic features from pointing in two clearly different directions. We will first predict using all the data from the kinematic markers if subjects had pointed upwards or downwards. Once we obtain success with this easier example which would serve as an essential proof of concept, we will move on to the more difficult task of automatic identification with the EMG time series for the pointing directions of 180°, 135°, 45°, and 0°.

3.1. The kinematics of pointing upwards vs. downwards

In this section we used the kinematic information from a marker placed on the index finger of subjects to classify if the subjects had pointed downwards (180°) or upwards (0°). The input vector for classification was a time series of the XYZ coordinates of this marker from the start of pointing movement to the maximum pointing amplitude. The classification accuracy obtained using LDA was 100%.

The next step was to use LDA_{diff} to identify the features which were most relevant to this classification. Figure 4 displays the difference vector obtained from comparing the LDA created representations at 180° vs. 0°. A visual inspection of the LDA difference vector showed a much bigger amplitude of LDA_{diff} for the Y coordinate, while the differences for the X and Z dimensions were very low. According to our hypothesis, this indicated that the features most altered between the 2 pointing directions were those associated with the Y coordinate while the time series from the X and Z coordinates stayed relatively unchanged. This hypothesis was confirmed by an attempt at classification with the *High Diff Kinematic time series* (time series of Y coordinates) vs. the *Low Diff kinematic time series* (time series of X and Z coordinates). Table 1 displays the classification results obtained from using the *High Diff* vs. *Low Diff kinematic times series*. The results show that the classification accuracy and hence separation between the *High Diff kinematic time series* is higher compared to those for the *Low Diff kinematic time series*. This difference in separation was confirmed using the Support Vector Machine (SVM) and Learning Vector Quantization (LVQ) algorithms for classification. The difference in accuracy for these two kinematic series was found to be significant using all three Machine Learning algorithms ($p < 0.01$, χ^2 test) (Table 1).

This answer of which kinematic variable was most altered, was obviously correct as the only axis of movement was upwards and downwards. We only used it as an example and proof that examining LDA_{diff} was able to reveal the most saliently altered variable in the time series.

3.2. Muscular alterations for pointing in different directions

Once we had tested our method of feature selection on the simpler kinematic case described above, we embarked on the more complex example of EMG activities for pointing in different directions. The directions tested were 180°, 135°, 45°, and 0°. In each case, we conducted a binary classification in order to see which muscle combinations were significantly altered with respects to pointing horizontally at 90°, the gravity neutral direction. The organization of the input vectors and the sampling methods used for the classification are described in the Methods section above. The classification accuracies obtained using LDA can be seen in Figure 3A. Following the classification, we once again computed the LDA_{diff} to obtain an idea of the muscle combination which had contributed significantly to the classification and the moments at which they did so. Unlike the case with the kinematic features where one feature stood out in a very prominent manner, the situation was more complex in the case of the EMGs. In Figure 5 we can see the difference vectors obtained from subtracting the representations for each binary classification. In the case of Figures 5A, B, for downward pointing, it can be seen that the muscles that contributed the most to the difference vectors are the deltoid muscles and the trapezius. The LDA_{diff} vector predicting pointing at 0° however (Figure 5D), would seem to indicate the involvement of a different muscle combination which had been modified with respects to pointing at 90°. This combination was more distributed, involving the Anterior and Medial deltoids, the Pectoralis major, Latissimus dorsi, Trapezius and Biceps brachii.

The next step taken was to apply the recurrent method described above to test if the combination of muscles with contributions from the *High Diff* vectors gave better classification results than those contributing from the *Low Diff* vectors. Table 2 displays the results of this test. The LDA classification with the *High Diff muscles* systematically gave better results than the *Low Diff muscles* for the binary classifications of pointing at 90° vs. 180°, 135°, 45°, and 0° (Table 2, $p < 0.01$, χ^2 test).

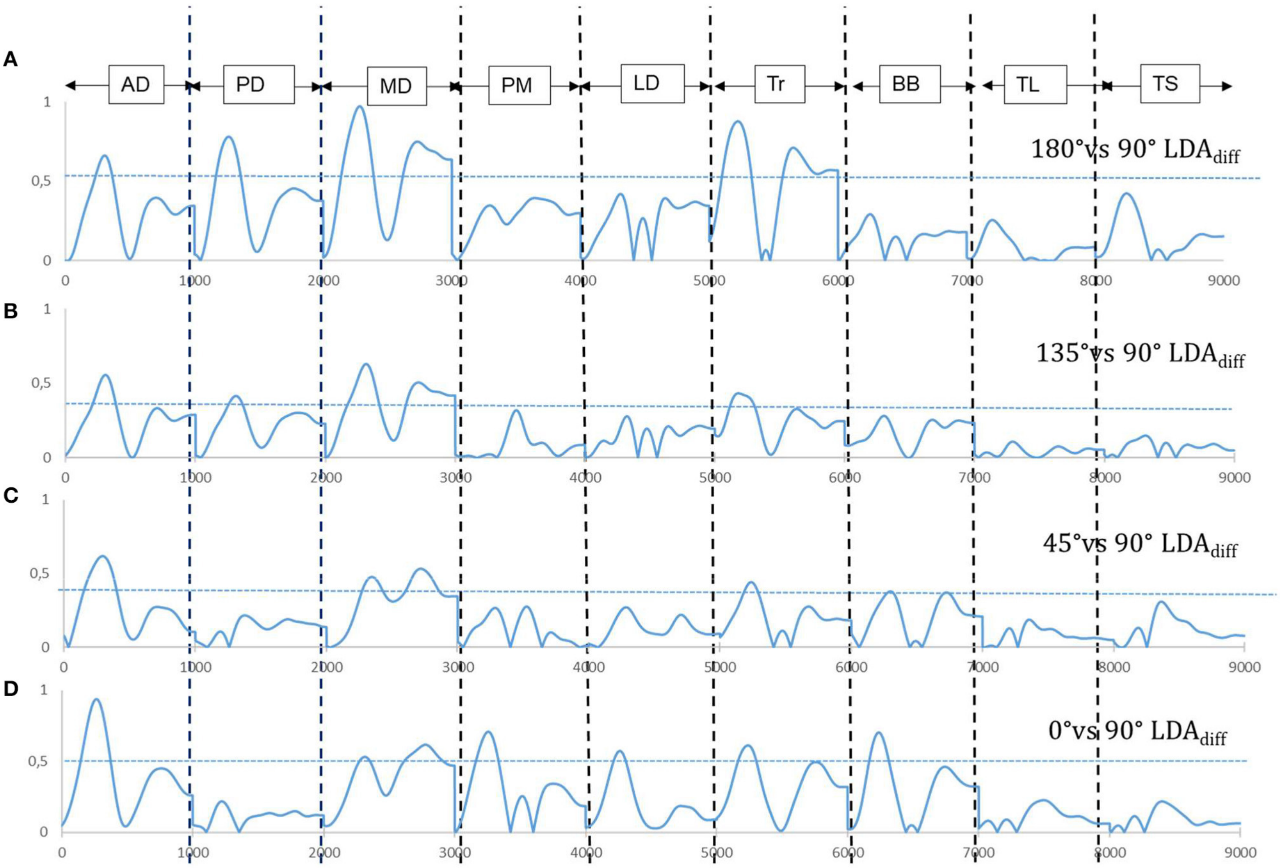

FIGURE 5
Difference vectors LDA_{diff} obtained from the binary classification of input muscle vectors pointing horizontally vs. at **(A)** 180° **(B)** 135° **(C)** 45° **(D)** 0°.

TABLE 2 Comparison of classification accuracies using the EMGs from the High Diff versus Low Diff muscles.

LDA				
	180°/90°	135°/90°	45°/90°	0°/90°
High Diff muscles	97	87.33	87.26	99.22
Low Diff muscles	79.89	60.81	58.44	58.18
SVM				
	180°/90°	135°/90°	45°/90°	0°/90°
High Diff muscles	100	93.11	91.96	98
Low Diff muscles	78.7	66.89	72.63	78.7
LVQ				
	180°/90°	135°/90°	45°/90°	0°/90°
High Diff muscles	97.5	87	87.32	99.64
Low Diff muscles	78.99	60.84	58.41	58.23

All values in the table are mean percentages.

Next we tested whether the information obtained concerning the important components of the input vector from the model comparison with LDA, would hold for another classification technique. For this, we now compared classification accuracies between the *High Diff* and *Low Diff muscles* using the Support Vector Machine (SVM) and Learning Vector Quantization (LVQ) algorithm. Once again, as in the case of LDA, classification accuracies were significantly higher using the *High Diff* muscles indicating that this combination of muscles were more significantly altered for pointing in different directions ($p < 0.01$, χ^2 test).

In Table 3 we have listed the *High Diff* and *Low Diff muscles* for pointing in various directions. They show that in all cases, the shoulder deltoid muscles were tuned to directional constraints. However, in comparison to the anterior and medial deltoid, the posterior deltoid did not play an important role in tuning toward the upward angles of 45° and 0°. Like the anterior and medial deltoid muscle, the trapezius muscle was important for modifications in all directions. In comparison to the other three angles, many more muscles were involved in the *High Diff* category for upward movement at 0°. Two additional trunk muscles, the latissimus dorsi and the pectoralis major played a more important role in this adjustment. For this direction, we also observed a bigger role for the biceps brachii. It has to be emphasized again that the lack of importance in classification does not indicate that a muscle is not activated during pointing. Instead it shows that there the activation difference between a muscle for the two angles being examined is not very marked.

TABLE 3 Muscles identified as *High Diff* or *Low Diff* muscles for each pointing angle.

High Diff and Low Diff muscles for pointing direction.		
Binary classification	*High Diff* muscles	*Low Diff* muscles
180° vs. 90°	Anterior, Medial and Posterior Deltoids, Trapezius	Pectoralis major, Latissimus dorsi, Biceps Brachi, Triceps short and long
135° vs. 90°	Anterior, Medial and Posterior Deltoids, Trapezius	Pectoralis major, Latissimus dorsi, Biceps Brachi, Triceps short and long
45° vs. 90°	Anterior Deltoid, Medial Deltoid, Trapezius	Posterior Deltoid, Pectoralis major, Latissimus dorsi, Biceps Brachi, Triceps short and long
0° vs. 90°	Anterior Deltoid, Medial Deltoid, Trapezius, Pectoralis Major, Latissimus Dorsi, Biceps Brachi	Posterior Deltoid, Triceps Long and Short

3.3. The LDA distance—a composite index of data separation

Classification accuracies provide a measure of data separability. High classification accuracies indicate that the data is highly separable and that the intra class variability is sufficiently low. On the other hand, once a certain amount of separability is present, classification accuracies would continue being high with a ceiling effect. One solution to this problem is to analyze the $LDA_{distance}$ in addition to classification accuracy. In Figure 3A, the classification accuracies at 180° and 0° were not found to be significantly different ($p > 0.05$, χ^2). This is not surprising as both accuracy values were similarly close to 100% (Table 2). Further information concerning data separation was obtained using the $LDA_{distance}$ variable. Figure 3B displays the mean values of the $LDA_{distance}$ obtained from the binary classifications of the EMGs from pointing at 90° vs. 180°, 135°, 45°, and 0°. While the classifications accuracies are similar for downward (180°) and upward (0°) pointing directions (Figure 3A), the $LDA_{distance}$ values show that when compared to pointing in the gravity free horizontal dimension, EMG adjustments with respects to horizontal pointing were greater when pointing downwards at 180 degrees than when pointing upwards at 0 degrees ($p < 0.05$, Friedmann, followed by Wilcoxon planned comparison).

3.4. The LDA_{diff} vector and temporal features

Rather than using concise representations of muscle EMGs such as the means or the maximum amplitude, we chose to keep the entire time series of EMG activity. This was so that the LDA difference vector LDA_{diff} would provide us with an understanding of the aspects of EMG activity which were altered not only in terms of amplitude but also in time. An inspection of LDA_{diff} for all the cases of binary classifications performed in the study showed that the biggest values of LDA_{diff} occurred in the first half of the movement. Once again, to test the idea that LDA_{diff} provides an index of feature importance, we took one muscle, the anterior deltoid, and compared classification accuracies for all the binary classifications with the first half of LDA_{diff} (*First Half temporal vector*) compared to the second half (*Second Half temporal vector*). The results of these classifications can be seen in Figure 6. The mean classification accuracies for all pointing directions were found to be greater in the first half of pointing. These differences however were not found to be significant when pointing in the downward directions (135° and 180°). The story however was different when pointing in the upward direction (45° and 0°), hence indicating that the most discriminable adjustments for pointing in these directions was at the start of pointing rather than in the latter half ($p < 0.01$, χ^2 and Bonferroni correction).

4. Discussion

In this study, we have investigated the use of Machine Learning as an analytical tool which is appropriate for investigating the big amounts of data gathered in motor studies. Whether it be with experimental equipment in labs or phone applications which accompany people in their daily activities, advances in data collection have led to the creation of vast banks of information. The collection of this data is in keeping with a willingness to abandon an approach in which investigation is only carried out on a narrow set of pre-decided variables. This then opens up a new problem—among the big set of collected variables, which ones are important to the task at hand? We propose here, the use of Machine Learning classification and feature selection as a means of identifying this subset. In the sections below, we will start out by explaining how the focus of this paper is fundamentally different from many previous papers combining EMGs and Machine Learning where the emphasis was on application. We will go on to explain our choice of LDA as a Machine Learning algorithm. We will further discuss our choice of feature selection methods and compare it to previous techniques and finally, we will discuss the results from the project in the context of our current understanding of muscular contributions to pointing.

When it comes to motor activity, the primary use of Machine Learning has been in the field of engineering, many of these for the control of prosthetic limbs or for improvements in patient identification. So for example, Côté-Allard et al. (2019) reported on how deep learning could be succesfuly used to recognize hand gestures. On a more challenging level, Parajuli et al. (2019) wrote a review in which they described several studies that used Machine Learning to control hand prostheses in real time. Still within the framework of application, several articles on methodological issues with respects to the use of EMGs in Machine learning applications have been written by Phinyomark and Scheme (2018) as well as by Xiong et al. (2021). Just as in the case of upper limb prosthetics, the use of Machine Learning with EMG signals from lower limbs have contributed to the control of prosthetics. This was described in a review article by Labarrière et al. (2021). A clinical study on how patients with arthritis could be identified through the use

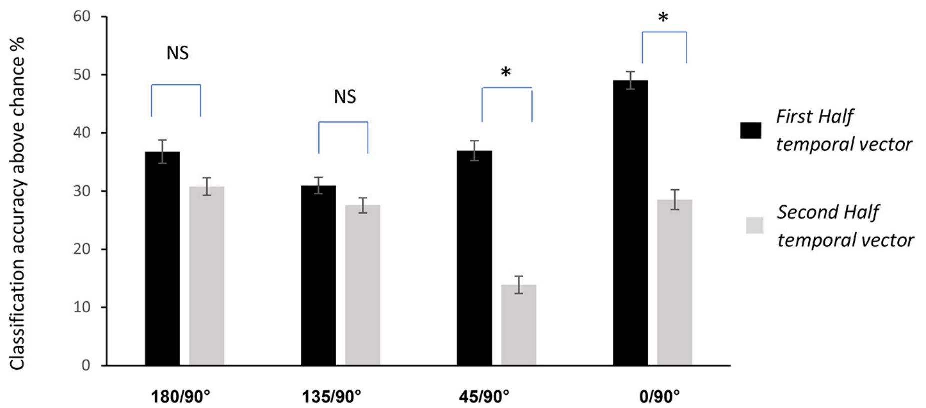

FIGURE 6
Classification accuracies obtained from the anterior deltoid EMG vector during the first and second half of the pointing movement. The figure shows that mean accuracies were higher in the first part of pointing. However, only the differences at 45° and 0° classifications were found to be significant ($p < 0.01, \chi^2$ and bonferroni correction). Values displayed are mean ± standard error of the mean. Significant results are indicated with an asterisk, while NS indicates non-significant results.

of lower limb EMGs and Machine Learning has been described by Nair et al. (2010). Cheron et al. (2003) described how lower limb kinematics could be mapped from lower limb EMGs using a recurrent neural network.

While the use of feature combinations in Machine Learning has proved to be useful in engineering applications, the approach can also be a way to tackle big data sets in basic research. By elucidating which features are important to discriminating task conditions, the technique can be used to identify the EMG or kinematic features which are the most altered between conditions. To our knowledge there has not been much research on the use of this approach in motor control. Some exceptions to this are studies by Tolambiya et al. (2011) where the SVM was used to analyze EMGs during Whole Body Pointing. The study showed that the *combination* of postural rather than focal muscles provided a better prediction of pointing constraints, hence demonstrating that postural, rather than focal muscles, underwent greater modifications for several different variants of the Whole Body Pointing task. Using the same approach, Tolambiya et al. (2012) showed in the anticipatory phase, that the *combination* of flexor rather than extensor muscles provided a higher than chance prediction between which of 4 different types of Whole Body Pointing tasks was about to be executed. This is indicative of differences in motor planning before the start of movement. In gait, Laroche et al. (2014) showed that the thigh sagittal angle was able to provide a discrimination of patients with hip osteoarthritis vs. control subjects as high as that of the combination of all other kinematic angles, hence indicating a high degree of modification in this angle for patients. These studies were able to exploit Machine Learning in the service of understanding how muscle and joint combinations contribute to motor control, hence presenting a departure from univariate studies. Nevertheless, the aforementioned studies on Machine Learning and EMGs are different from the current study in two important aspects. Firstly, the data combinations to be tested were decided upon *a priori* as opposed to this study in which the importance of variable combinations emerged from the feature selection that was done after (*a posteriori*) Machine Learning. Secondly, since classification in the previous studies was done with pre-selected groups, an ensemble view that allowed us to obtain an idea of the relative contributions of each muscle and phase with respects to the entire dataset as in Figure 3 was not obtained.

In this study we put an emphasis on the use of LDA as a classification algorithm. Several previous studies, including some of our own, have shown that other methods such as the kernel methods which include SVMs or random forest are more efficient classifiers (Díaz-Uriarte and Alvarez de Andrés, 2006; Statnikov et al., 2008; Nair et al., 2010; Heung et al., 2016; Han et al., 2017; Uddin et al., 2019; Chen et al., 2020). Another example more pertinent to motor control is a study by Aeles et al. (2020) in which they used the SVM to uniquely distinguish between 78 individuals using their EMG signatures (Aeles et al., 2020). Indeed Tables 1, 2 of this study show that the SVM provides better classification. However such efficient classification would yield poor information regarding the proximity of EMG data for pointing in different directions as the SVM is capable of exploiting very small differences to yield high classification i.e. we would face a ceiling effect. Our choice was therefore to move ahead with LDA with which classification accuracy would provide more information concerning data overlap and because of the ease with which we were able to perform feature selection. This is also more in keeping with the spirit of explainable artificial intelligence (XAI) (Murdoch et al., 2019; Arrieta et al., 2020). Although it goes under the guise of this new name, XAI, the attempt to give a priority to understanding the factors which permitted the black box of artificial intelligence to achieve its classification and hence obtain an understanding of underlying mechanisms is not new (Chan et al., 2002; Nair et al., 2010; Tolambiya et al., 2011, 2012). It should be pointed out that even a classification of 80% yields a statistical significance of $p < 0.01$ (χ^2 test). The LDA algorithm, being a method which relies on the creation of multivariate Gaussians models of each class, allows for the subtraction of representations and a quick visualization of the role of each feature in discrimination. This difference also provides a means of quantifying the distance between classes. As opposed to this, the SVM and Random Forest are methods that rely on a more distributed representation whereby this technique of representation subtraction cannot be used so readily. We have cited here several studies in which methods which are based on decision trees like Random Forest, achieve a superior performance. Once again, this method is not ideal when we are dealing with long time series (the concatenated EMGs) from which we do not wish to pick out particular features *a priori*.

While we were able to apply LDA to this problem of motor control with healthy subject in a repeated measures or paired protocol (same subjects pointing at all angles), it should be noted that not all data sets would be so linearly discriminable. This might especially be the case for studies with independent groups like patients and controls. Patient data also tends to have high variability. In such cases, if we are to follow the logic of post-classification feature selection, the characteristics of the separating surface can be used to select the most discriminating features (Guyon et al., 2002; Weston et al., 2003).

LDA has been used for feature selection using all three paradigms described in the Introduction section. An example of the filter method was an investigation by Lei et al. (2012) where the Fisher criterion was used to select the most discriminative features before application of LDA for face discrimination. An example of the wrapper method applied with LDA can be seen in the study by Gayathri and Sumathi (2016) where feature combinations were assembled *a priori* and then tested with LDA. We did not apply either of these techniques as they were not in keeping with our wish to have a method in which the importance of feature *combinations* is derived from the classification algorithm itself. A successful classification indicates the presence of important discriminating features and finding these features yields the required variable combination

The muscles playing important roles in tuning for different pointing directions are listed in Table 3. They are all the deltoid muscles in the downward directions, along with the trapezius muscle. In the upward direction, the posterior deltoid no longer plays a key role, while two additional trunk muscles, the pectoralis major and latissimus dorsi contribute to pointing at 0°, compared to 90°. This is in keeping with previous studies which have shown these muscles to have different activities as a function of pointing directions (Flanders, 1991; Flanders et al., 1996, 196; Mira et al., 2021). The novelty in the current study is that we have used Machine Learning to pick out the muscles among the collection of recorded muscles which are most pertinent to altering pointing directions and highlighted when these changes occur. This is not a trivial consideration as this would increase the ease of visualization and model construction especially for more complex movements. This would then improve the characterization of movements in healthy subjects and hence draw attention to compensatory movement patterns that might indicate early onset of neuromuscular deficiencies. Another novel aspect of the current study was the introduction of the $LDA_{distance}$ variable that provided a means of understanding certain global characteristics of EMG alterations for pointing directions. For example, overall EMG adjustments for pointing in the upward direction were lower than those for the downward direction when compared to horizontal pointing. The higher $LDA_{distance}$ at 180° in Figure 3B demonstrates this. This may be due to the fact that, although horizontal and upward movements follow a classical tri-phasic burst organization (Hallett et al., 1975; Virji-Babul et al., 1994), downward movements do not do so (Gaveau et al., 2021). Gaveau et al. (2021) have provided several arguments to show that this is perhaps because gravity replaces the agonist burst to accelerate the arm downwards, thereby saving muscle effort. Downward movements therefore exhibit activation patterns that strongly deviate from the classical tri-phasic burst pattern (Gaveau et al., 2021; Poirier et al., 2022a). Thus, the temporal organizations of upward and horizontal movements are more similar to each other than are those of downward and horizontal movements.

Concerning the roles of the individual muscles as seen in Table 3, the importance of the deltoid muscles in classification would be due to their role in setting the direction for the different angles of pointing. It is striking that the posterior deltoid while playing a key role in tuning for downward pointing is less important in tuning for upward pointing. During the acceleration part of upward and horizontal (rightwards) movements, substantial activity of the posterior deltoid muscle is needed to respectively stabilize the joint and accelerate the arm (Gaveau et al., 2021). During downward movements, however, this muscle remains largely silent. Again, the fact that the effort from the posterior deltoid is replaced by gravity torque, during a downward movement, makes the pattern of this muscle very different from its activation during a horizontal one. Regarding why the latissimus dorsi is useful in classifying upward but not downward movements compared to horizontal ones, we may say that it may be due to the fact that this muscle is engaged in stabilizing the shoulder joint and decelerating the arm when moving upwards. On the contrary, this muscle is less if any activated during downward (its effort is replaced by gravity torque) and horizontal movements (it is perpendicular to the plane of motion). The relatively low prominence of muscles such as the biceps and triceps acting around the elbow joint might be due to the protocol of the experiment in which elbow rotation was discouraged. This is in contrast to the experiments conducted by the Flanders group (Flanders, 1991; Flanders and Herrmann, 1992; Buneo et al., 1994, 2008; Flanders et al., 1996) where a pointing protocol with elbow rotations was involved. The important role played by the trapezius muscle for modulation in both directions is in agreement with reports by other groups that along with the anterior deltoid, it plays an important role in shoulder orientation for pointing direction (Sabatini, 2002; Tokuda et al., 2016). It should be noted that none of the differences in contribution to classification here is due to differences in EMG amplitude as this variable is normalized (see Methods).

The EMGs in this study were classified without picking any particular properties of the EMG. Only the classic pre-processing of rectification, smoothing and filtering to remove noise was applied. There are of course several techniques from signal analysis which could be used to extract particular time and frequency dependant characteristics of the signal. Such methods are for example, Fourier transforms or wavelet analyses. Many engineers have applied wavelet analyses to the analyses of EMG patterns, once again with the primary goal of successfully discriminating between movements types or populations (Phinyomark et al., 2011; Sharma and Veer, 2016; Koenig et al., 2018). Future studies could involve the use of such techniques, more with the goal of understanding the underlying mechanisms of movement. In such studies we would aim to trace how specific EMG properties are shifted as a function of arm pointing direction. While there may not be any big changes in the types of frequencies involved in the contraction involved, the wavelet technique with its extraction of information concerning when particular frequencies come into play, holds more promise for revealing changes in muscle activity with direction.

In conclusion we will say that in the era of big data, Machine Learning Classification with LDA appears to be a useful tool which can complement currently available techniques like univariate statistics and PCAs in the study of motor control. Univariate statistics which are the most widely employed analytical tool in motor control studies have been extremely useful in confirming or rejecting pre-conceived notions on important variables. This technique is less viable in the face of big volumes of data and less open to the possibility of previously unexpected influences. The use of ensemble techniques like PCA and non negative matrix factorization, used to find synergies have been extremely useful in tackling the problem of the number of degrees of freedom in the motor system (d'Avella et al., 2010, 2011; Delis et al., 2018). They have a completely different goal from the current paper. They aim to construct a common framework from which to describe various types of movement while the goal of the current project is to find differences. It should also be pointed out that the two methods are not incompatible. Once synergies are constructed, Machine Learning classification can then be used to assign classes based on the synergies.

Data availability statement

The data analyzed in this study will be made available upon request. Requests to access these datasets should be directed to Jeremie.Gaveau@u-bourgogne.fr.

Ethics statement

The study was approved by the Regional Ethics Committee of Burgundy. The patients/participants provided their written informed consent to participate in this study.

Author contributions

ET contributed to the conception of problem for machine learning and manuscript preparation. FA conducted analyses and contributed to manuscript preparation. JG contributed to data collection, conception of analyses, and manuscript preparation. FC and AT contributed to machine learning conception and manuscript preparation. All authors contributed to the article and approved the submitted version.

Funding

This work was supported by 2021PRE00389_2021Y-09560_CAPS _IACM_FONC. In this grant from the Conseil Régional of Bourgogne Franche Comté there is a budget line for open access publication. This research has been funded in part by the Institut National de la Santé et de la Recherche Médicale (INSERM) of France and by the Conseil Régional de Bourgogne.

Conflict of interest

AT was employed by Accenture Solutions Private Ltd.

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

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