What happens in the prefrontal cortex? Cognitive processing of novel and familiar stimuli in soccer: An explanatory fNIRS study

Dissertation

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Table of contents

Presentation of research topic

Introduction

The superiority of sport experts in different disciplines has been studied over decades (1). It is fascinating to clarify the „characteristics, skills, and knowledge that distinguish experts from novices and less experienced people" (2) and result in outstanding performance of experts in a specific field (3). Current research focuses increasingly on the role of cognition in expert performance (3, 4). Especially perceptual-cognitive abilities seem to be decisive for expert performance in sports (5). One of the two traditional theoretical approaches that systematically investigates expert performance in sports was created by Ericsson and Smith (1991), known as the "expert performance approach" (6, 7). It represents a descriptive and inductive process that involves a three-stage process for analyzing expert performance including (i) the capture of expert performance, (ii) identifying underlying mechanisms and (iii) examining the development of expertise (8). This approach focuses exclusively on expert performance in a sport-specific field (7). On the contrary, the "cognitive component skill approach" by Nougier et al. (1991) considers the relationship between sports expertise and non-sport-specific, so called general cognition (7, 9, 10). Earlier research has shown that experts outperform novices in both general cognitive tests (11, 12, 13) and sport-specific cognitive test situations (14, 15, 16). With increasing expertise, changes in cortical activity were detected (17). Despite the scientific indications of the superior cognitive abilities of experts, it is not yet sufficiently clarified which and to what extent, changes in cortical activity underlie athletic expertise (3, 4).

The prefrontal cortex

The prefrontal cortex (PFC) is a frequently studied region of interest in perceptual-cognitive processing. It is responsible for a variety of higher cognitive functions, such as cognitive control and executive functions (18, 19). The prefrontal cortex (PFC) is a complex brain region composed of distinct units, each with its unique characteristics (20). Recent neuropsychological research focused on patterns of prefrontal activity during different cognitive demands, more precisely, the cortical processing of novel versus familiar stimuli. Every part of the PFC possesses its own network of connections that sets it apart from other areas (18). Lateral and dorsolateral areas of the PFC are seem to be primarily responsible for processing of novel stimuli, as evidenced by increased activity during general perceptual-cognitive tests (21, 22)

and novel task learning (23). In contrast, cognitive tests that contain familiar aspects showed increased activity changes in the anterior and dorsomedial PFC (22, 24, 25).
“Repetition suppression” is one of the most thoroughly researched phenomena in neuroscience, indicating that repetition of (similar) stimuli results in a general reduction in cortical activity (4, 26, 27, 28). Confirmedly, decreased activity was found in patients when naming repeated or familiar objects compared to new objects (29). Furthermore, after exposure to a novel stimulus for three times, a decrease in activity in the PFC was already evident, similar to what was observed within familiar stimuli (27). This highlights the involvement of PFC in automated cognitive processing, as further evidenced by reduced activity in the dorsolateral PFC during the transition from controlled to automated decisions (30, 31). These studies underline the complexity of the PFC, showing different activity patterns during processing of novel and familiar or automated cognitive tasks.

Cortical processing of experts and novices

Current research focuses increasingly on the role of cognition and the underlying cortical mechanisms in expert performance (3). Sport psychologists utilize the “expert-novice-paradigm” to investigate expert performance, aiming to understand the psychological, biological, and social factors that influence optimal performance (32). This is accomplished by comparing experts to novices and/or conducting within-experts investigations.

In sports-specific cognitive tasks, experts resort to specialized cognitive abilities and automated strategies related to the characteristics of their discipline (33). This results in superior performance of experts in sport-specific memory, attention, anticipation and decision-making skills compared to novices (15, 16, 28, 34). Furthermore, several studies found that elite (team) athletes outperform novices even in general cognitive tests (12, 13, 35, 36). However, the underlying cognitive mechanisms for expertise in the respective discipline have not been sufficiently researched yet (3, 37). Investigations of athletes’ cortical activity in general and sport-specific cognitive testing yielded heterogeneous results.

General Cognition

Expertise research identified different prefrontal activity patterns during general cognitive tasks between experts and novices. Previous research in sports detected during general cognitive tasks increased activity in the dorsolateral PFC, as shown in working memory tasks in archery experts (38) and a sustained attention task in martial arts experts (33). Sanchez-Lopez et al.

(2014) provided an initial investigation into different prefrontal mechanisms within experts during novel and automated cognitive tasks, comparing prefrontal activity in sustained versus transient attention in martial arts experts. Increased activity during sustained and decreased activity during transient attention tasks was detected. Since sustained attention relies on controlled responses, they concluded that transient attention involves more automated and less controlled processes (33). These results are consistent with spatial activity changes described for novel stimuli (4).

Sport-specific cognition

Prior research on the cortical activity of experts and novices in sport-specific cognitive tasks found deviating results. The "neural efficiency theory" assumes higher cortical effectivity in experts during sport-specific cognitive tasks (28, 39). This theory is based on research by Haier et al. (40) who investigated the relationship between neural activation and performance in intelligence tests. He discovered lower glucose metabolism levels in subjects who performed better in intelligence tests, suggesting cortical mechanisms that enabled increased efficiency (17). Higher neural efficiency is characterized by selective attention on task-relevant processes and inhibition on interfering stimuli, and results from only recruiting the necessary spatial cortical areas to perform the cognitive task (28, 41). Additionally, the effective switching between the recruitment of current necessary brain areas and the suppression of non-relevant brain areas is described in the "neural proficiency theory" (32).

Along with these theories, experts were found to have decreased prefrontal activity compared to novices in sport-specific cognitive tasks (28, 42). However, deviating studies reporting increased cortical activity during sport-specific attention and anticipation tasks exist (43, 44). These results differ significantly from each other and the neuropsychological findings on familiar stimuli (4).

Perceptual-cognitive abilities in soccer

Soccer is a dynamic sport demanding rapid decisions in complex game situations (45, 46). Expert soccer players make the right decisions more often and carry out actions efficiently throughout the game (47). This fast and accurate decision-making seems to be the basis for intelligence and expertise in soccer (48).

Before athletes make decisions, they have to perceive situations and process information. This emphasizes that expert performance is also based on exceptional perceptual-cognitive and motor skills (8, 45). Research suggests that executive functions (EF) and selective attention are particularly important, with elite team athletes outperforming novices in these areas (7, 49).

In soccer, studies have shown correlations between executive functions, attention tasks and soccer performance (12, 13, 37, 45). Elite and semi-athlete players significantly outperform amateurs in EF tasks, with elite players exceeding semi-alite players as well (13). Furthermore, EF performance correlated with future goals and assists (13, 50). These findings, consistent across adolescent and adult elite, highlight the crucial role of perceptual-cognitive skills throughout a soccer career (13). Given the importance of perceptual-cognitive functions for expertise in soccer, the chosen field of research appears to be suitable for investigating the underlying cortical mechanisms of expertise (4).

Quantifying cortical activity and cognitive functions in sports experts

Functional near-infrared spectroscopy (fNIRS)

To gain a deeper understanding of expertise, an examination of the brain activity of experts during general and sport-specific situations could be elucidating (4). Functional near-infrared spectroscopy represents a valid tool for indirect measurement of cortical activity, and thus offers an appropriate alternative to functional magnetic resonance topography (fMRI) (51). This emerging optical neuroimaging technique measures the concentration changes of oxy-Hb and deoxy-Hb in brain tissue taking advantage of the relatively high transparency of brain tissue between 650 – 900 nm wavelength, the so called “optical window”, and the characteristic hemoglobin absorption spectra in these wavelengths (52, 53). During measurements, fNIRS diodes’ point near-infrared light on the scalp and detect emerging light levels simultaneously (54). Based on the different absorption spectra of the two chromophores of hemoglobin (oxy-Hb and deoxy-Hb), possible changes in concentration can be determined with the help the modified Beer-Lambert law (53). Since neural activity is associated with increased local vasodilation resulting in an inflow of oxygenated hemoglobin into the vessel, an increase in oxy-Hb and a decrease in deoxy-Hb in the fNIRS measurement can be considered to indicate an activated brain area (55).

Despite the existing disadvantages of fNIRS, namely the inability to detect subcortical activity and missing anatomical information, the validity of fNIRS measurements could be confirmed comparing fNIRS signals with fMRI measurements (54, 56, 57). Benefitting of its portability, movement tolerance and non-invasive-utilization, fNIRS outplays other neuroimaging methods in the research of brain activity during motion-intensive situations such as walking, daily activities and sports (51, 56, 58, 59).

In 2020, Menant et al. published updated guidelines on data collection and processing, highlighting the importance of proper hardware set-up, minimizing motion-related artifacts, and transparent processing and reporting of fNIRS data (52). Most recently, NIRS has also been applied in expert research to understand the cortical processing of experts and to provide a greater understanding of expertise in the future (58).

Vienna Test System (VTS)

The Vienna Test System (VTS, Schuhfried GmbH, Mödling, Austria) is a computer-based system that offers an objective method for evaluating general, non-sport-specific, perceptual-cognitive abilities and personality traits (37, 60). It consists of interactive assessments that have been proved to be a reliable and valid method to analyze and identify cognitive activities as reaction, attention, anticipation, peripheral perception and stress reactivity (60, 61). Frequently, the VTS has been used to investigate differences in cognitive abilities between athletes and novices and athletes from different levels (60). This enabled, for instance, to detect differing reaction times and peripheral vision in volleyball players as compared to novices (62).

The determination test (DT) of the VTS measures “the reactive stress tolerance and the corresponding reactive ability” (63) and has been utilized in several studies (61, 64). During the DT, participants differentiate between various visual and acoustic signals and press the correspondent buttons on the panel. Existing literature highlights limitations and methodological inconsistencies in current research using the VTS, particularly the use of different VTS subtests to measure the same cognitive ability across various studies. This must be considered when interpreting the results of different subtests (60). However, due to its objectivity, the VTS undoubtedly enables the potential for future applications in the field of sport psychology research (60).

Witty SEM System

The Witty SEM System (Witty SEM, Microgate GmbH, Bolzano, Italy) represents an alternative tool of assessing cognitive skills with the advantage of adding motor aspects to the examination (65, 66, 67, 68). Consequently, the Witty SEM System enables tests of both general and sport-specific cognition in motion (65, 66, 67, 69). It consists of semaphores, which can be placed individually and display different colored shapes and numbers (67). At the same time, they contain motion sensors which can be triggered by a hand movement in front of the semaphores (65). These technical possibilities enable measuring complex processes of motor response to visual stimuli, which can also be integrated with sport-specific characteristics such as dribbling or passing a ball (66, 67).

The "Agility" test measures reactivity and decision-making as a sport-specific test situation. The subject rapidly passes the ball against the one of three back-pass walls that presents a green square. The back-pass walls are positioned in a semicircle around the subject with a radius of 4 meters (4, 69). The "Hawk Eye" test examines cognitive decision-making and sustained attention in a non-sport-specific test in motion. The subject stands in front of a 2 by 3 meters big wall and chooses the one out of eight visual stimuli at a wall, that is deferring in terms of color by moving its hand in front of it (4, 67).

The Witty SEM system is a promising tool for evaluating athletes' cognitive skills in motion-intensive test situations. Its ability to adept tests to replicate sports-specific game situations offers a valuable advantage. However, the systems reliability for measuring cognitive skills needs further investigations as only some tests has been verified yet. Further research is needed to fully explore its capabilities for cognitive assessments in athletes (65).

Study aims

The aim of this study was to compare cortical processing of general and sport-specific cognition within experts by measuring hemodynamic changes in the PFC. It embodies a relevant approach to provide information about the underlying mechanisms of expertise. To our knowledge, no studies have yet conducted intrapersonal comparisons of the cortical activity of experts in both general and sport-specific cognition so far.

Main findings

The results of the study indicate higher cortical activity during general cognitive tasks compared to sport-specific tasks in soccer experts. Significant differences were mainly observed in the dorsolateral PFC during the computer-based tests and throughout the entire PFC during the test in motion. The observed activity changes during general cognition are consistent with previously reported findings on novel stimuli. The reduced activity during sport-specific cognitive tasks may suggest a decreased use of the PFC, leading to increased efficiency. This seems to be in line with the “repetition suppression theory”, the “neural efficiency theory” and the “neural proficiency hypothesis”. Assuming that lower cortical activity changes are due to automated processes and enhanced efficiency, it can be hypothesized that the advantage experts show over novices in sport-specific cognitive tasks is due to improved automated neural processes. The observed differences in cortical activity during general and sport-specific tasks may potentially result from altered prefrontal structures in experts. The make-up of prefrontal processing could be a decisive factor for expertise in team sports.

Future studies and implications

This study demonstrates a first approach to indirectly visualize the cortical activity of experts. However, more evidence is needed to strengthen these findings. To address the issue of different cortical possesses of experts and novices, in the future, intrapersonal studies on both experts' and novices' prefrontal activity during general and sport-specific cognition are needed to clarify whether expertise is due to structurally different mechanisms in the cortex. These studies should be conducted even in regard to age, position-specific and sex differences. Furthermore, further research is needed to improve the reliable application of fNIRS in motion.

Information about the underlying mechanisms of athletic expertise could be used for optimizing future training methods to enhance athletic performance. Characterizing brain activity of elite athletes during general or sport-specific cognition could discover and/or monitor weaknesses and strengths, resulting in adaptations in individual training regimes (70). Furthermore, information on the cortical make-up of experts could be used for talent selection, enabling the early detection of promising young athletes with the potential for future success in its sport (3, 8, 70). Soccer classifies as a strategic sport. However, static disciplines like shooting and interceptive sports like boxing also require significant perceptual-cognitive abilities with distinct cognitive profiles (71). Therefore, research on the cortical makeup of soccer experts could be transferred to other team and individual sports in the future.

Furthermore, these findings in expertise research have the potential to extend beyond the domain of sports and be applied in the healthcare sector. Developing optimized training protocols to promote cognitive automatisms could be beneficial for fall prevention in elderly populations. Additionally, information on brain activity patterns of expert in a surgical field could be utilized in future surgical training approaches.

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What happens in the prefrontal cortex? Cognitive processing of novel and familiar stimuli in soccer: An exploratory fNIRS study

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ABSTRACT
The importance of both general and sport-specific perceptual-cognitive abilities in soccer players has been investigated in several studies. Although these perceptual-cognitive skills could contribute significantly to soccer players' expertise, the underlying cortical mechanisms have not been clarified yet. Examining activity changes in the prefrontal cortex under different cognitive demands may help to better understand the underlying mechanisms of sports expertise. The aim of this study was to analyse the prefrontal activity of soccer experts during general and sport-specific cognitive tasks. For this purpose, 39 semi-professional soccer players performed four perceptual-cognitive tests, two of which assessed general cognition, the other two assessed sport-specific cognition. Since soccer is a movement-intensive sport, two tests were performed in motion. While performing cognitive tests, prefrontal activity was recorded using functional near-infrared spectroscopy (fNIRS) (NIRSport, NIRx Medical Technologies, USA). Differences of prefrontal activity in general and sport-specific cognitive tasks were analysed using paired t-tests. The results showed significant increases in prefrontal activity during general cognitive tests (novel stimuli) compared to sport-specific tests (familiar stimuli). The comparatively lower prefrontal activity change during sport-specific cognition might be due to learned automatisms of experts in this field. These results seem in line with previous findings on novel and automated cognition, "repetition suppression theory" and "neural efficiency theory". Furthermore, the different cortical processes could be caused by altered prefrontal structures of experts and might represent a decisive factor for expertise in team sports. However, further research is needed to clarify the prefrontal involvement on expertise in general and sport-specific cognition.

Highlights

- This fNIRS study examines differences in the prefrontal activity of soccer experts during general and sport-specific cognitive tasks.
- In general cognitive tasks, increased prefrontal activity changes were detected, whereas lower cortical activity changes during sport-specific cognition were found.
- These findings support the "repetition suppression theory" and earlier findings on the processing of novel stimuli in the prefrontal cortex (PFC).
- The differences in the cortical processing of general and sport-specific tasks of soccer players might be caused by altered prefrontal structures of experts and could be of special importance for expertise in soccer.

KEYWORDS
Cognition; motor control; neuroscience; performance; skill

Introduction

The superiority of experts in various sport disciplines has been studied over decades (Araújo et al., 2019). Current research focuses increasingly on the role of cognition in expert performance (Mann et al., 2007; Moran et al., 2019). It has been shown that experts perform better than novices in general cognitive tests (Scharfen & Memmert, 2019) and in sport-specific cognitive test situations (Wimshurst et al., 2016). Despite the scientific evidence of the superior cognitive abilities of experts, it is not yet sufficiently clarified which and to what extend changes in cortical activation underlie expertise (Moran et al., 2019). These findings could help to gain information about the cortical makeup of experts and the associated cortical mechanisms that could condition higher expertise. In the future, such knowledge could possibly be taken into account in talent selection as well as in talent development. Although neurodiagnostic examination of athletes using functional near-infrared imaging (fNIRS) in sports-relevant domains has already been requested by current research (Seidel-Marzi & Ragert, 2020), studies of brain activity in sport-specific and

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general test situations have barely been conducted to date. These studies may help to better understand the underlying cortical mechanisms of expertise.

The prefrontal cortex (PFC) is a frequently studied region of interest in perceptual-cognitive processing of both novel and familiar stimuli. Studies in primates examined the time course of neural activity in the PFC and found increased activity in reaction to new stimuli compared to familiar objects (Rainer & Miller, 2002). Accordingly, lateral and dorsolateral areas of the PFC are primarily responsible for processing novel stimuli, as evidenced by increased activity during general perceptual-cognitive tests (Barbey & Patterson, 2011; Cole et al., 2017) and novel task learning (Cole et al., 2016). Moreover, "repetition suppression" is one of the most thoroughly studied phenomena in neuroscience (Auksztulewicz & Friston, 2016; Soldan et al., 2010) showing that repetition of (similar) stimuli is associated with a general reduction in cortical activity (Soldan et al., 2010; Li & Smith, 2021). Confirmedly, decreased activity was found in patients when naming repeated objects compared to new objects (Korzeniewska et al., 2020). Along with the "repetition suppression theory" (Soldan et al., 2010), research on prefrontal involvement in automated cognitive processing found a reduced activity in the dorsolateral PFC during the transition from controlled to automated decisions (Jansma et al., 2001; Erdeniz & Done, 2019). These studies illustrate that different regions of the PFC show different activity patterns during processing novel and familiar or automated cognitive tasks. Nevertheless, it is not yet understood to what extent these neuropsychological findings can be transferred to expertise research in sports and thus contribute to the clarification of the underlying mechanisms of sport expertise. In this study, we hypothesise that general cognitive tasks for soccer experts consist mainly of novel stimuli while sport-specific tasks represent familiar stimuli.

Investigations of athletes' cortical activity in general and sport-specific cognitive testing yield heterogeneous results. Comparing experts and novices in sports, prior research found increased activity in the dorsolateral PFC during general cognitive tests on working memory in archery (Seo et al., 2012) and a sustained attention task in martial arts experts (Sanchez-Lopez et al., 2014). Sanchez-Lopez et al. (2014) offered a first approach to identify different prefrontal mechanisms within experts during novel and automated cognitive tasks, comparing the prefrontal activity during sustained and transient attention in martial arts experts. Increased activity during sustained and decreased activity during transient attention tasks was detected. Whereas sustained attention is based on controlled responses, they concluded that transient attention can be attributed to automated and less controlled processes. These results are consistent with spatial activity changes described for novel stimuli.

In contrast, deviating results were obtained on the cortical activity of sport-specific tasks between experts and novices. The "neural efficiency theory" (Li & Smith, 2021) assumes higher cortical effectivity in experts during sport-specific cognitive tasks through selective attention on task-relevant processes and inhibition of interfering stimuli (Li & Smith, 2021; Perrey, 2022). Additionally, the effective switching between the recruitment of current necessary brain areas and the suppression of non-relevant brain areas is described in the "neural proficiency theory" (Filho et al., 2021). Along with these theories experts were found to experts were found to have decreased prefrontal activity in sport-specific cognitive tasks compared to novices (Li & Smith, 2021; Perrey, 2022; Olsson & Lundström, 2013). However, deviating studies reporting increased cortical activity exist (Filho et al., 2022; Wei & Luo, 2010).

However, the comparison of prefrontal activity among experts and novices reveals expected differences during the processing of general and sport-specific cognitive tests, which could be reflected in the superiority of the experts. To gain a deeper understanding of expertise, an examination of the brain activity of experts-only in both cognitive situations (sport-specific and general tests) could be elucidating. Based on both the "repetition suppression theory" and the "neural efficiency theory", we assume increased activity in the dorsolateral PFC during the processing of novel stimuli in general cognitive tasks and decreased activity in the sport-specific cognitive task. To our knowledge, no study has examined and compared the prefrontal activity of experts in these cognitive demands so far.

Our study embodies a relevant approach to provide information about prefrontal mechanisms of general and sport-specific cognition in soccer experts which could result in a deeper understanding of the underlying prefrontal mechanisms of expertise. We assessed prefrontal activity of semi-professional soccer players in two general and two sport-specific cognitive tasks with functional near-infrared spectroscopy (fNIRS). Soccer players must constantly make rapid decisions in dynamic and complex game situations (Ehmann et al., 2022; Wang et al., 2020). Due to this perceptual-cognitive expertise they represent a valid subject group for this study. Soccer represents a movement-intensive sport. Even during casual walking, locomotor pathways are activated resulting in changes of the cortical activity (Herold et al., 2017; Khan et al., 2021). Therefore, in order to represent the expertise of soccer experts in its full complexity, it is necessary to investigate cortical activity under the influence of physical activity. For this reason, two out of four tests were performed in motion. To ensure prefrontal involvement, the tests demanded higher cognitive functions as decision-making and selective attention (Menon & D'Esposito, 2022). Near-infrared spectroscopy represents a valid tool for indirect measurement of cortical activity, with certain limitations even in motion (Tan et al., 2019; Quaresima & Ferrari, 2019; Menant et al., 2020). As fNIRS is more frequently used in motion-intensive situations in sports and exercise research (Phillips et al., 2023), recent studies are focusing on improving fNIRS data quality and classification in motion-intensive situations (Hamid et al., 2022; Nazeer et al., 2020).

The aim of this study was to compare cortical processing of general and sport-specific cognition within experts by measuring hemodynamic changes in the PFC. As described in the "expert performance approach" (Starkes & Ericsson, 2003) sport-specific tasks are designed to be similar to the athlete's environment and appear familiar to the experts. On the other hand, general attention tasks are assumed to be a novel situation. According to the "repetition suppression theory" (Auksztulewicz & Friston, 2016) and "neural efficiency theory" (Li & Smith, 2021) we hypothesised increased activation in the PFC during general cognitive tasks and decreased prefrontal activity during the sport-specific cognitive tests. Examining the neural processing of familiar stimuli, it must be assumed that their processing is partly based on automated processes (Sanchez-Lopez et al., 2014).

Materials and methods

Participants

39 semi-professional male soccer players, aged 18–33 years (M = 24.85 ± 4.00 years) participated in this study. Since it is now proposed to qualify the performance of athletes based on competition level rather than sole hours of soccer experience (Scharfen & Memmert, 2019), participation in a semi-professional soccer league (4th to 6th highest leagues) in Germany represents the primary inclusion criterion. All adult participants had binocular vision, no motoric or psychiatric impairments and no arterial hypertonus. Participants were excluded from calculations if channel quality was bad, indicated by a CV > 7.5%. A power analysis using G*Power 3.1.9.2 (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, 2014) resulted in a mean comparison of two dependent groups with an α-level = 0.05, an effect size d = 0.8 and a targeted power of 0.95 to a subject number of n = 23. Based on anticipated channels with bad quality a total of 39 subjects participated in the tests in motion to enable the inclusion of 23 participants into calculations, while 26 subjects thereof participated in the computer-based tests. The study was conducted at the Institute of Human Movement Sciences at the University of Hamburg, Germany. Table 1 presents the demographics of the participants. This study was ethically approved by the local ethics committee of the Faculty of Psychology and Human Movement Sciences, University of Hamburg (AZ 2017_106). All participants provided written informed consent before participating in this study. The study followed the principles of the Declaration of Helsinki.

Procedure

The present study aimed to compare the cortical activity in general and sport-specific cognitive tasks in soccer experts. For this purpose, participants completed four perceptual-cognitive tests described below, which are classified into sport-specific and general cognition. Each category included one computer-based test and one test in motion. The participants completed the test battery standardised instructed in the same order (sport-specific computer-based test, non-sport-specific computer-based test, non-sport-specific test in motion, sport-specific test in motion). The self-developed sport-specific computer-based test (SSC) was performed within a test-retest design twice, as the first and last test, to examine the reliability. The test order remained equal for each participant to minimise possible influence of physical activity on cognitive performance, which could appear by randomising test order (Pontifex et al., 2019). Meanwhile, the prefrontal activity was measured using fNIRS. To avoid the influence of increased blood flow (Herold et al., 2017), both heart rate (Polar RS400, Polar Electro Oy, Kempele, Finland) and blood pressure were measured before each trial to insure adequate resting in between. The total testing duration was approximately 60 min.

Brain activity

To measure the prefrontal activity a multi-channel continuous fNIRS system (NIRSport, NIRx Medical Technologies LLC, New York, USA) with eight laser sources, eight photo detectors and a sampling rate of 8.7193 Hertz was used. To allow a topographical mapping of

Table 1. Descriptives of participants.

Characteristic	N = 39 male
Age [years]	24.85 ± 4.00
Height [cm]	182.13 ± 6.67
Weight [kg]	78.47 ± 8.20
Body mass index [kg/m^2]	23.62 ± 1.65
Soccer experience [years]	19.10 ± 3.56

the different Brodmann areas, a 21-channel configuration was placed on the PFC (Figure 1) with an inter-optode distance of three centimetres. The resulting channels (area between one source and one detector) were subdivided into three PFC areas (frontomedial PFC: Channel (Ch) 11, 17–19; ventrolateral PFC: Ch 15–16, 20–21; dorsolateral PFC: Ch 1–10, 12–14) based on EEG 10–20 mapping (Öngür & Price, 2000; Petrides, 2005). The activity 15 s prior to the test during a resting state was measured (baseline) to enabled a comparison to the hemodynamic situation during perceptual-cognitive tests (Herold et al., 2017). Thereafter, the respective starting point was marked in the fNIRS recording.

Non-sport-specific (general) cognition

Non-sport-specific computer-based test (NSSC) (Figure 2A). The NSSC examines reactivity and decision-making to visual and auditory stimuli in a non-sport-specific computer-based test ("Determination Test", Vienna Test System, Schuhfried GmbH, Mödling, Austria). The participant distinguishes between different coloured stimuli and acoustic signals and selects the correspondent buttons on the panel. The median reaction time within 3 min of testing time is measured.

Non-sport-specific test in motion (NSSM) (Figure 2B). The NSSM measures cognitive decision-making and sustained attention in a non-sport-specific test in motion ("Hawk Eye", Witty SEM, Microgate GmbH). The subject stands in front of a 2 by 3 metres big wall and chooses the one out of eight visual stimuli at a wall, that is deferring in terms of colour by moving its hand in front of it. The number of right decisions within 30 presented stimuli is measured.

Sport-specific cognition

Sport-specific computer-based test (SSC). The SSC examines rapid decision-making in a sport-specific, computer-based test situation. 40 still images out of professional soccer matches are being presented to the subject. The task involves rapidly deciding the best option of the player in possession of the ball to score (shoot, pass or dribble) by pressing the respective button on the keyboard. Both accuracy and speed of decision-making are considered by documenting the total processing time and the number of right answers.

Sport-specific test in motion (SSM) (Figure 2C). The SSM measures reactivity and decision-making as a sport-specific test situation in motion ("Agility" Witty SEM, Microgate GmbH, Bolzano, Italy). The subject rapidly passes the ball against the one of three back-pass walls that presents a green square. The back-pass walls are positioned in a semicircle at 0°, 45° and 90° around the subject with a radius of 4 metres. The total time required for 40 passes is and the median reaction time is measured.

Data processing of fNIRS signal

The fNIRS data was prepared for statistical calculation with the nirsLab software (nirsLab 2019.4, NIRx Medical Technologies, New York, USA). To reduce signal artefacts and physiological noise (heartbeat and breathing) a

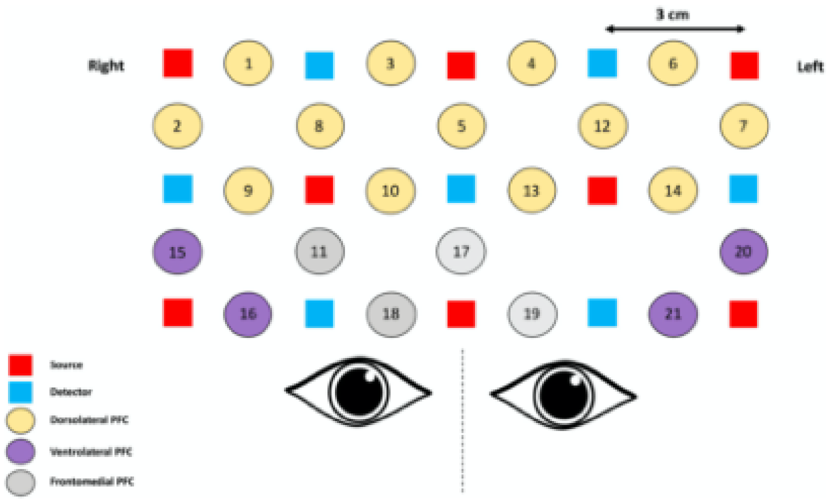

Figure 1. Topographical mapping of the channels attached to the PFC. PFC, prefrontal cortex; DL, dorsolateral; VL, ventrolateral; FM, frontomedial.

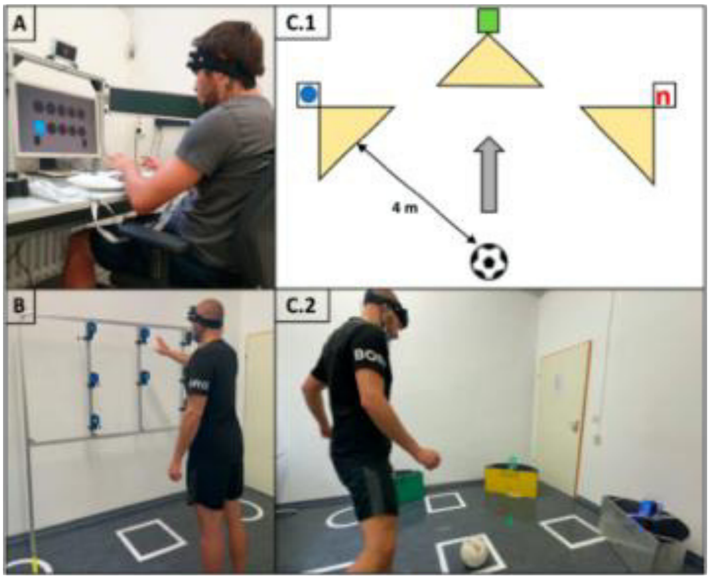

Figure 2. Illustration of the structure and processing of the NSSC (A), NSSM (B) and SSM (C.1 and C.2). C.1 shows a schematic setup of the SSC while C.2 pictures the actual execution of the tests. n, changing numbers 1–9.

band pass filter (low cut-off frequency: 0.01 Hertz; high cut-off frequency: 0.2 Hertz) was adjusted (Piper et al., 2014; Herold et al., 2017, 2018). A light signal variance (CV) of less than 7,5% is required for an adequate signal quality for evaluation. Therefore, only channels fulfilling this criterion could be included for further analyzation. As conducted in prior studies (Pinti et al., 2018; Herold et al., 2017), the first 45 s of the test periods were considered and divided into three time blocks of 15 s each. A default duration of the baseline was set as 15 s (Herold et al., 2018). The recorded data of each channel were transformed to hemodynamic data based on the parameters of the Beer–Lambert Law (W. B. Gratzer, London). Average oxyhaemoglobin (oxy-Hb) values of the baseline and each time block within the 21 channels were calculated.

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics 26® (IBM®, Armonk, New York, USA). To examine the time window of the greatest cortical change, only the second time block (15–30 s after start) was considered (Pinti et al., 2018). Relative oxygenation changes of oxy-Hb between baseline and testing period were calculated in each channel. A paired t-test between computer-based tests (NSSC vs. SSC) was conducted to detect differences in the cortical processes between sport-specific and general cognition. Similarly, a paired t-test examined differences in cognitive tests in motion (NSSM vs. SSM). Mean (M) and standard deviation (SD) values were calculated for all participants demographics and hemodynamic data. To test the reliability of the self-developed SSC-test, the intraclass correlation (ICC) was calculated. Referring to Koo and Li (2016) values less than 0.5 indicate poor reliability, values between 0.5 and 0.75 represent a moderate reliability, values between 0.75 and 0.9 indicated good reliability and values greater than 0.90 indicated excellent reliability.

Results

Means, standard deviations and paired t-tests of computer-based cognitive tests (SSC and NSSC) and tests in motion (NSSM and SSM) in channel 1–21 are shown in Tables A1 and A2. The intraclass correlation of the SSC resulted in ICC = 0.71. This can be valued as a moderate reliability. Results of the behavioural data of all tests can be seen in Table A1.

Computer-based tests (SSC and NSSC) (Figure 3A; Table A2)

Frontomedial PFC. A significant difference was found in channel 19 ($t(14) = -2.41$, $p = 0.03$) with an increased mean activity during the NSSC ($M = 4.32$, $SD = 7.363$) compared to the SSC ($M = 0.61$, $SD = 3.69$). No significant difference was observed in Channel 11, 17 and 18.

Ventrolateral PFC. There was no significant difference between the relative activity changes in SSC and NSSC in the ventrolateral PFC.

Dorsolateral PFC. There were significantly increased activity changes during the general cognitive task (NSSC) in channel 1 ($t(18) = -2.91$, $p = 0.01$), channel 3 ($t(23) = -3.09$, $p < 0.01$), channel 4 ($t(23) = -3.30$, $p < 0.01$), channel 5 ($t(22) = -2.17$, $p = 0.04$), channel 12 ($t(23) = -3.63$, $p < 0.01$) and channel 14 ($t(23) = -2.74$, $p = 0.01$). While performing the sport-specific task (SSC) the prefrontal activity showed a significantly smaller increase or even a decrease in activity.

Tests in Motion (SSM and NSSM) (Figure 3B; Table A3)

Frontomedial PFC. Significant differences were found in channel 11 ($t(9) = 2.54$, $p = 0.04$) and 17 ($t(9) = 3.49$, $p < 0.01$). Comparable with the computer-based tests, the general cognitive test (NSSM) showed an increased activity (Ch 11: $M = 3.60$, $SD = 4.26$; Ch 17: $M = 5.17$, $SD = 2.64$), whereas smaller increase in channel 17 ($M = 0.72$, $SD = 1.74$) or even a decrease in activity in channel 11 ($M = -0.83$, $SD = 4.71$) was detected during the sport-specific test (SSM). There were no significant results in channel 18 and 19.

Ventrolateral PFC. In contrast to the computer-based tests, all channels except for channel 16 showed a significant difference in the activity during general (NSSM) and sport-specific (SSM) tests in motion (Ch 15: $t(7) = 6.45$, $p < 0.01$; Ch 20: $t(13) = 2.30$, $p = 0.04$; Ch 21: $t(13) = 2.22$, $p = 0.05$). There was decreased mean activity during the sport-specific test (SSM) in all channels.

Dorsolateral PFC. Significant differences were found in the activity of channel 1 ($t(15) = 2.24$, $p = 0.04$), 2 ($t(4) = 3.99$, $p = 0.03$), 3 ($t(19) = 3.16$, $p < 0.01$), 4 ($t(24) = 3.58$, $p < 0.01$), 6 ($t(4) = 3.58$, $p = 0.04$), 12 ($t(17) = 3.73$, $p <$

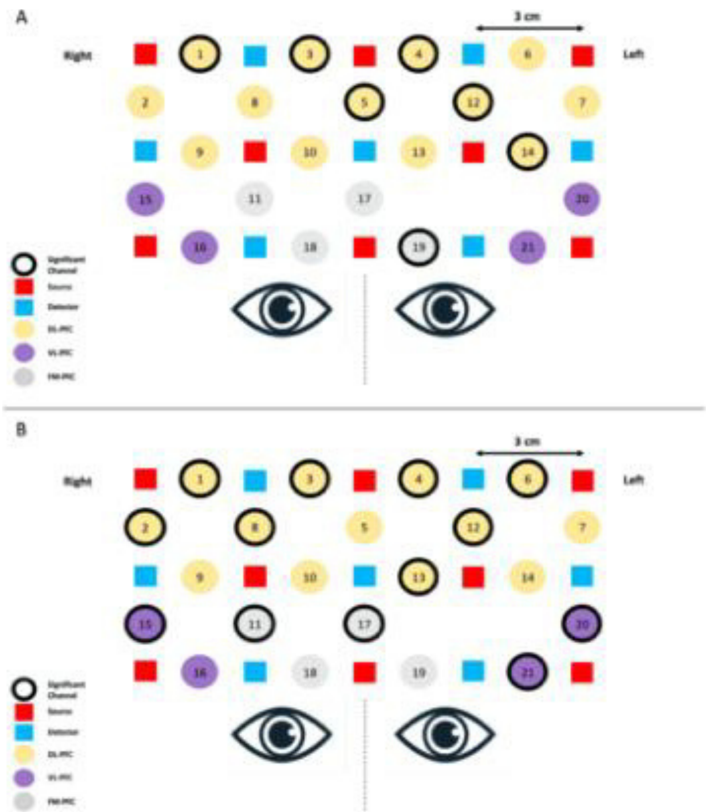

Figure 3. Topography of significant channels in computer-based cognitive tests (NSSC vs. SSC) (A) and cognitive tests in motion (NSSM vs SSM) (B). NSSC, non-sport-specific computer-based test; SSC, sport-specific computer-based test; PFC, prefrontal cortex; DL, dorsolateral; VL, ventrolateral; FM, frontomedial.

0.01) and 13 ($t(21) = 3.94$, $p < 0.01$) as well as in computer-based tests. Additionally, channel 8 ($t(20) = 2.39$, $p = 0.03$) showed significantly increased activity in the general cognitive task in motion (NSSM). No significant differences were observed in channels 5, 7, 9, 10 and 14.

Discussion

In this study, the prefrontal activity of soccer experts in general and sport-specific cognitive tasks was examined and compared using fNIRS in order to elucidate the underlying cortical mechanisms of expertise. Significant differences in PFC activity between general and sport-specific cognitive tasks were found primarily in the dorsolateral PFC in the computer-based tests and throughout the PFC in the tests in motion. As assumed, the results indicate higher cortical activity during general cognitive tasks compared to sport-specific tasks in soccer experts.

These results of activity changes during general cognition are consistent with previously reported findings on novel stimuli (Barbey & Patterson, 2011; Cole et al., 2017). In line with these studies, we found increased cortical activity predominantly in the dorsolateral PFC when processing novel stimuli in the general cognitive test. During decision processes, the lateral PFC is involved in the generation of possible solutions and the subsequent evaluation of the best solution (Barbey & Patterson, 2011; Ghanavati et al., 2019). More specifically, the dorsal part of it, namely the dorsolateral PFC, is strongly interconnected with cortical areas responsible for processing visual, motor and auditory information (Barbey & Patterson, 2011; Ghanavati et al., 2019). These characteristics of the dorsolateral PFC could explain the isolated activity increase in this area during the general cognitive task, as no preformed solutions are yet available for the soccer player and these have to be newly developed. This suggests that the findings on prefrontal processing of novel stimuli, which are represented in investigations with other populations and experts outside the sports, can also be confirmed for sports experts.

In sport-specific tasks, as described, a decreased prefrontal activity of experts was found. These results may indicate a decreased use of the PFC and consequently increased efficiency (Eggenberger et al., 2016). This is in line with the "repetition suppression theory", according to which soccer experts recognise repetitive stimuli from their soccer experience during sport-specific cognitive tasks, resulting in decreased cortical activity (Li & Smith, 2021; Korzeniewska et al., 2020; Auksztulewicz & Friston, 2016; Soldan et al., 2010). The applicability of this theory in sport psychology can hereby be confirmed. It also supports the "neural efficiency theory" and "neural proficiency hypothesis", which describe higher cortical efficiency through lower cortical activity during sport-specific cognition in experts (Li & Smith, 2021; Filho et al., 2021).

Assuming that a lower activity change is due to automated processes and leads to increased efficiency, it can be hypothesised that the advantage experts show over novices in sport-specific cognitive tasks is due to improved automated neural processes. An indication for this is provided by the results of Sanchez-Lopez et al. (2014), who report a lower cortical activity during automated cognitive processes in experts compared to novices. This is supported by transient hypo-frontality, as part of the "neural proficiency hypotheses" in sport-specific tasks describing decreased frontal activity, which indicates strong reduction of conscious and deliberate thinking (Filho et al., 2021). The present results of the computer-based cognitive tests thus may hint that experts process general and sport-specific cognitive tasks through different cortical mechanisms. This could be due to the greater expert experience or frequent experience of the sport-specific situations of experts, which leads to a transformation of cognitive processes into automatisms (Fitts & Posner, 1967). It may be assumed that otherwise novices process both tasks in the same prefrontal area since no transition to automated cognitive processing would have occurred and both stimuli would appear to be novel stimuli for them. On the other hand, controversially, some studies reported increased activity in the PFC of experts in both general cognitive tasks (Seo et al., 2012) and sport-specific cognitive tests (Wei & Luo, 2010; Wright et al., 2010), suggesting that experts have increased prefrontal activity in both cognitive demands compared to novices. To address the issue of different cortical processes of experts and novices, in the future, intrapersonal studies on both experts' and novices' prefrontal activity during general and sport-specific cognition are needed to examine expert and novice groups and thus clarify whether expertise is due to structurally different mechanisms in the cortex. However, we only examined the change in cortical activity of experts in different test situations, so the difference in activity changes between experts and novices cannot be substantiated in this study.

Comparing the results of the computer-based tests and the tests in motion, it can be seen that the localisation of the significant activity changes differs. As in computer-based tests, increased prefrontal activity was measured during the general cognitive test in motion. However, these changes were not limited primarily to the dorsolateral PFC, but were found in all regions of the PFC (including frontomedial and ventrolateral PFC). Previous studies of prefrontal activity during motion predominantly found increased prefrontal activity due to activation of the indirect locomotor pathway, which includes the PFC (Herold et al., 2017, 2018). On the other hand, Hamacher and colleagues (2015) reported that, opposite to this, a decreased prefrontal activity in motion could occur based on the transition from controlled to automatic gait which goes along with a shift from the indirect to the direct locomotor pathway (Eggenberger et al., 2016). Since movement-intensive sports, such as soccer, are better represented sport-specifically in physically active test situations, these tests include even more automated stimuli for the soccer player. The combination of the high amount of automated processes and the activation of the direct locomotor pathway might explain the significant decreases of activity in all areas of the PFC during the sport-specific tests in motion. However, this explanation must be further investigated in future studies. To better classify the results of the cognitive tests in motion, the measurement technique with fNIRS, which is suitable for measurements in physical activity (Pinti et al., 2018), must be further discussed. Looking at the number of included datasets in the individual channels of the cognitive tests in motion, one can see fewer numbers of included subjects than in the computer-based tests, especially in channels with significant differences. This is due to poor data quality (CV > 7.5%). The poor data quality can be attributed to motion-associated parameters, such as motion artefacts or physiological noise (Orihuela-Espina et al., 2010; Herold et al., 2017). Although the heart rate was controlled before each test and data were filtered with a recommended band-pass filter, it is questionable whether these provisions are sufficient to reduce false positives (Orihuela-Espina et al., 2010; Herold et al., 2017). In summary, data from tasks involving larger movements seem to be less reliable (Menant et al., 2020). Accordingly, the application of innovative methods to improve data quality and the development of further techniques is needed to reliably represent cortical activity changes in motion and to confirm the existing results (Menant et al., 2020; Hamid et al., 2022; Nazeer et al., 2020).

Limitations of our study need to be considered regarding the application of fNIRS. First, a weakness of fNIRS represents the lack of anatomical information (Cutini et al., 2012). Our topographic assignment of diodes is based on the established EEG 10–20 system. However, it cannot be assured that the mapping corresponds exactly to the cortical areas. Further research is needed to show which areas are mapped by the placed fNIRS diodes. Second, Herold and colleagues (2017) highlight the possibility of mind wandering during baseline measurement which can distort the values (Durantin et al., 2015). As recommended (Herold et al., 2018) a baseline measurement of 10–30 s in a quiet, seated position was conducted. The suggestion of a simple counting task during baseline measurement (Holtzer et al., 2015) to prevent mind wandering could be a solution for future analyses. Moreover thus far, there is no consensus about the most suitable temporal window to capture the greatest activity change during the time course in the PFC (Orihuela-Espina et al., 2010; Herold et al., 2018). Due to the fact that hemodynamic responses are usually 3–5 s delayed, (Orihuela-Espina et al., 2010) we chose the period 15–30 s after the start of testing as the measurement interval. Further studies are needed to investigate the optimal measurement intervals for various fNIRS protocols depending on the investigated area and question.

Practical implications

The lower prefrontal activity in sport-specific tasks compared to general cognitive tasks indicates a lower cognitive effort in the expert's PFC when performing this task. Considering this assumption, varying the cognitive demands in training by incorporating unknown cognitive stimuli could lead to an improved training effect. By varying and increasing the cognitive demands in training, the athlete could develop greater flexibility and further automatisms to cope with the cognitive demands in game situations.

Conclusion

This study aimed to analyse prefrontal mechanisms in general and sport-specific cognition tasks in soccer experts. Experts showed an increased activity in general cognitive tasks compared to sport-specific cognitive tasks in both computer-based tests and tests in motion. It could be assumed that these different cortical processes are caused by altered prefrontal structures of experts. The prefrontal processing structure could be a decisive factor for expertise in team sports. This study demonstrates a first approach to indirectly visualise the cortical activity of experts and provides evidence supporting the "repetition suppression theory" in sports science and the "neural efficiency theory". However, more evidence is needed to strengthen these findings. Future studies should investigate both experts' and novices' brain activity during general and sport-specific cognition even with regard to age, position-specific and sex differences.

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No potential conflict of interest was reported by the author(s).

Author contributions

Conceptualisation: Nils Schumacher, Lena Schmaderer. Data acquisition: Lena Schmaderer, Mathilda Meyer. Statistical analysis: Lena Schmaderer. Methodology: Nils Schumacher, Lena Schmaderer. Project administration: Nils Schumacher. Resources: Rüdiger Reer. Visualisation: Lena Schmaderer, Mathilda Meyer. Writing original draft: Lena Schmaderer, Nils Schumacher. Writing – review & editing: Lena Schmaderer, Nils Schumacher, Mathilda Meyer.

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Appendix A

Table A1. Behavioural data of the participants.

Test		n	Variables	M ± SD	Min–Max
SSC	t1	39	Correct answers	28.8 ± 2.1	25–34
			Total time [sec]	102.6 ± 34.8	67–287
	t2	37	Correct answers	29.0 ± 2.25	24–33
			Total time [sec]	71.4 ± 22.0	48–193
SSM		39	Median RT [sec]	1.5 ± 0.1	1.3–2.0
			Total time [sec]	67.9 ± 8.8	52.4–89.2
NSSC		37	Median RT [sec]	0.7 ± 0.05	0.6–0.8
NSSM		39	Correct answers	29.4 ± 0.71	28–31

Means, standard deviations and range of main variables in SSC t1 (pre-test), SSC t2 (post-test), SSM, NSSM and NSSC (version S1 and S3).

M, mean; SD, standard deviation; min, minimal value; max, maximal value; RT, reaction time; n, number of subjects.

Table A2. Paired t-test of fNIRS data (oxy-Hb) between SSC and NSSC.

Computer-based cognitive tests		SSC	NSSC	Paired t-test	
Channel	n	M (SD) [mmol/l*10^{-3}]	M (SD) [mmol/l*10^{-3}]	T	p
1	18	−0.902 (3.978)	3.861 (6.245)	−2.913	0.010**
2	9	−2.735 (6.558)	3.795 (8.098)	−1.809	0.108
3	23	0.211 (3.061)	3.376 (3.780)	−3.086	0.005**
4	23	0.527 (3.633)	3.785 (4.945)	−3.304	0.003**
5	22	0.018 (3.334)	1.970 (3.526)	−2.167	0.042*
6	11	−1.315 (5.713)	4.351 (6.177)	−2.175	0.055
7	10	−3.061 (11.178)	7.979 (14.747)	−1.917	0.087
8	21	0.633 (4.934)	1.899 (6.449)	−0.764	0.454
9	10	−0.437 (5.484)	0.699 (6.136)	−0.373	0.718
10	22	−0.259 (4.240)	1.592 (4.799)	−1.541	0.138
11	11	1.124 (3.849)	2.057 (4.445)	−0.754	0.468
12	23	−0.933 (3.995)	3.383 (5.636)	−3.625	0.001**
13	21	−0.577 (3.710)	1.876 (6.179)	−2.031	0.056
14	23	−0.960 (5.147)	3.535 (6.941)	−2.735	0.012*
15	8	−0.623 (3.514)	−0.625 (6.391)	0.001	0.999
16	16	−1.092 (5.404)	3.099 (9.104)	−1.688	0.112
17	11	−0.001 (3.998)	0.223 (3.897)	−0.197	0.848
18	10	−0.293 (5.359)	2.780 (9.614)	−1.643	0.135
19	14	0.614 (3.690)	4.320 (7.363)	−2.414	0.031*
20	16	0.806 (2.911)	2.420 (5.3488)	−1.615	0.127
21	13	0.649 (3.766)	3.275 (9.227)	−1.393	0.189

FNIRS, functional near-infrared spectroscopy; oxy-Hb, oxyhaemoglobin; SSC, sports-specific computer-based test; NSSC, non-sport-specific computer-based test.

*$p \leq 0.05$, **$p \leq 0.01$.

Table A3. Paired t-test of fNIRS data (oxy-Hb) between NSSM and SSM.

Cognitive tests in motion		NSSM	SSM	Paired t-test	
Channel	n	M (SD) [mmol/l*10^{-3}]	M (SD) [mmol/l*10^{-3}]	T	p
1	15	1.706 (5.194)	−2.149 (5.876)	2.240	0.042*
2	4	3.809 (2.415)	−4.578 (5.025)	3.992	0.028*
3	19	4.085 (4.425)	−0.038 (4.468)	3.163	0.005**
4	24	4.188 (3.805)	0.148 (4.966)	3.569	0.002**
5	22	2.763 (5.746)	0.771 (3.442)	1.917	0.069
6	4	0.467 (4.289)	−3.863 (3.569)	3.576	0.037*
7	5	1.443 (10.772)	−4.483 (7.911)	2.611	0.059
8	20	3.111 (6.173)	0.045 (4.283)	2.392	0.027*
9	12	2.399 (6.299)	0.508 (2.777)	1.124	0.285
10	21	0.767 (3.799)	0.226 (3.617)	0.541	0.595
11	9	3.600 (4.262)	−0.828 (4.710)	2.538	0.035*
12	17	2.434 (4.597)	−0.825 (3.816)	3.729	0.002**
13	22	3.030 (4.899)	−0.139 (3.533)	3.942	0.001**
14	18	3.796 (6.066)	1.279 (4.275)	1.647	0.118
15	7	2.659 (4.097)	−2.006 (3.281)	6.449	0.001**
16	14	5.120 (7.922)	0.268 (5.439)	1.919	0.077
17	9	5.170 (2.639)	0.715 (1.740)	3.486	0.008**
18	8	4.926 (0.768)	1.393 (4.960)	1.474	0.184
19	11	1.750 (6.375)	0.147 (5.215)	0.673	0.516
20	13	2.625 (4.832)	−0.992 (3.592)	2.296	0.040*
21	13	4.552 (7.739)	−1.588 (5.555)	2.221	0.046*

FNIRS, functional near-infrared spectroscopy; oxy-Hb, oxyhaemoglobin; NSSC, non-sport-specific computer-based test, SSC, sports-specific computer-based test

*$p \leq 0.05$, **$p \leq 0.01$

Summary

English version

The aim of this dissertation was to examine activity changes in the prefrontal cortex of experts under different cognitive demands, to help understand the underlying mechanisms of sport expertise. Previous studies have found that both general and sport-specific perceptual-cognitive skills contribute significantly to expertise in soccer. Therefore, this study investigated the prefrontal activity of 39 semi-professional soccer players, during general and sport-specific cognitive tasks. Since soccer is a movement-intensive sport, two out of four tests were performed in motion. While performing cognitive tests, prefrontal activity was recorded using functional near-infrared spectroscopy (fNIRS) (NIRSport, NIRx Medical Technologies, USA). Differences of prefrontal activity in general and sport-specific cognitive tasks were analyzed using paired t-tests.

The results showed significant increases in prefrontal activity during general cognitive tests (novel stimuli) compared to sport-specific tests (familiar stimuli). The results of activity changes during general cognition are consistent with previously reported findings on novel stimuli. The comparatively lower prefrontal activity changes during sport-specific cognition might be due to increased efficiency and learned automatisms of expert in this area. This seems to be in line with the "repetition suppression theory", the "neural efficiency theory" and the "neural proficiency hypothesis". The observed differences in cortical activity during general and sport-specific tasks could potentially be caused by altered prefrontal structures in experts. The prefrontal processing structure could be a decisive factor for expertise in team sports, but further research is needed to strengthen our finding.

In this purpose, intrapersonal studies on both experts' and novices' prefrontal activity during general and sport-specific cognition should be conducted to clarify, whether expertise is due to structurally different mechanisms in the cortex. Furthermore, age, position-specifics and gender differences must be taken into account. Information about the underlying mechanisms of athletic expertise could be used for optimizing future training methods, talent selection and could even have the potential to extend beyond the domain of sports and be applied in the healthcare sector.

German version

In dieser Dissertation wurden Aktivitätsveränderungen im präfrontalen Kortex von Experten bei unterschiedlichen kognitiven Anforderungen untersucht, um zugrunde liegenden Mechanismen sportlicher Expertise zu verstehen. Frühere Studien haben gezeigt, dass sowohl allgemeine als auch sportartspezifische wahrnehmungskognitive Fähigkeiten signifikant zur Expertise im Fußball beitragen. Daher wurde in dieser Studie die präfrontale Aktivität von 39 semiprofessionellen Fußballspielern während allgemeiner und sportspezifischer kognitiver Aufgaben analysiert. Da Fußball eine bewegungsintensive Sportart ist, wurden zwei von vier Tests in Bewegung durchgeführt. Während der Durchführung der kognitiven Tests wurde die präfrontale Aktivität mittels funktioneller Nahinfrarotspektroskopie (fNIRS) aufgezeichnet (NIRSport, NIRx Medical Technologies, USA). Mithilfe von gepaarten t-tests wurden die Unterschiede in der präfrontalen Aktivität bei allgemeinen und sportartspezifischen kognitiven Aufgaben analysiert.

Die Ergebnisse zeigten eine signifikante Zunahme der präfrontalen Aktivität bei allgemeinen kognitiven Tests (neue Reize) im Vergleich zu sportartspezifischen Tests (bekannte Reize). Die Ergebnisse der Aktivitätsveränderungen während allgemeiner kognitiver Tests, stimmen mit den zuvor berichteten Ergebnissen zu neuen Reizen überein. Die geringere Veränderung der präfrontalen Aktivität während der sportartspezifischen Kognition könnte auf gesteigerte Effizienz durch erlernte Automatismen von Experten in diesem Bereich zurückzuführen sein. Diese Ergebnisse scheinen mit früheren Erkenntnissen aus der "Repetition suppression theory", und der "Neural efficiency theory" übereinzustimmen. Darüber hinaus könnten die unterschiedlichen kortikalen Prozesse auf veränderte präfrontale Strukturen von Experten basieren und ein entscheidender Faktor für die Expertise im Mannschaftssport darstellen. Es bedarf jedoch weitere Forschung, um diese Erkenntnisse zu stützen.

Zukünftig sollten intrapersonelle Studien zur präfrontalen Aktivität von Experten und Novizen während allgemeiner und sportartspezifischer Kognition durchgeführt werden, um zu klären, ob Expertise auf strukturell Unterschiede im Kortex zurückzuführen ist. Alters-, positionsspezifische und geschlechtsspezifische Unterschiede sollten dabei berücksichtigt werden. Informationen über die zugrundeliegenden Mechanismen sportlicher Expertise könnten für die Optimierung zukünftiger Trainingsmethoden und die Talentauswahl genutzt werden und das Potenzial haben, über den Bereich des Sports hinaus, zum Beispiel im Gesundheitssektor Anwendung zu finden.

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Abbreviations

DT	Determination test
EF	Executive functions
fNIRS	Functional near-infrared spectroscopy
fMRI	Functional magnetic resonance topography
PFC	Prefrontal cortex
VTS	Vienna test system

Author contributions

Dr. Nils Schumacher administered the study, which was conducted at the "Institute of Movement Sciences" at the University of Hamburg, under the medical direction of Prof. Dr. Rüdiger Reer. Lena F. Schmaderer and Dr. Nils Schumacher initially developed the concept of the project, the study design and methodological approach. They also programmed the necessary tests of the Witty SEM system and created the sport-specific computer-based test "SSC". The four cognitive tests were conducted on 39 semi-professional soccer players by Lena F. Schmaderer and Mathilda Meyer. The subsequent statistical analysis was calculated by Lena F. Schmaderer and critically evaluated by both Lena F. Schmaderer and Dr. Nils Schumacher. Lena F. Schmaderer and Dr. Nils Schumacher wrote the initial draft of the manuscript, while Lena F. Schmaderer and Mathilda Meyer were responsible for all visualizations. Lena F. Schmaderer, Dr. Nils Schumacher and Mathilda Meyer critically review and edited the final the manuscript.

Eidesstattliche Versicherung

Ich versichere ausdrücklich, dass ich die Arbeit selbständig und ohne fremde Hilfe, insbesondere ohne entgeltliche Hilfe von Vermittlungs- und Beratungsdiensten, verfasst, andere als die von mir angegebenen Quellen und Hilfsmittel nicht benutzt und die aus den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen einzeln nach Ausgabe (Auflage und Jahr des Erscheinens), Band und Seite des benutzten Werkes kenntlich gemacht habe. Das gilt insbesondere auch für alle Informationen aus Internetquellen.
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Die „Stellungnahme des Präsidiums der Deutschen Forschungsgemeinschaft (DFG) zum Einfluss generativer Modelle für die Text- und Bilderstellung auf die Wissenschaften und das Förderhandeln der DFG“ aus September 2023 wurde dabei beachtet.
Ferner versichere ich, dass ich die Dissertation bisher nicht einem Fachvertreter an einer anderen Hochschule zur Überprüfung vorgelegt oder mich anderweitig um Zulassung zur Promotion beworben habe.

Ich erkläre mich einverstanden, dass meine Dissertation vom Dekanat der Medizinischen Fakultät mit einer gängigen Software zur Erkennung von Plagiaten überprüft werden kann.

Datum

23.09.2024

Unterschrift

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