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# The relationship of cognitive functions with physical skills, game intelligence, game time and its training in elite soccer players

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Affidavits following §7 section 2 No. 4 and 5 of the doctoral regulations from the German Sport University Cologne, February 20th 2013:

Hereby I declare:

The work presented in this thesis is the original work of the author except where acknowledged in the text. This material has not been submitted either in whole or in part for a degree at this or any other institution. Those parts or single sentences, which have been taken verbatim from other sources, are identified as citations.

I further declare that I complied with the actual “guidelines of qualified scientific work” of the German Sport University Cologne.

Hans-Erik Scharfen, Cologne, January 31th, 2022

# Abstract

Investigations of high-performance environments evaluate the qualities that make the best the best. One of these environments is elite sport representing one of the biggest challenges for the human brain as it demands a range of multifaceted aspects like the information processing of the cognitive functions. In this thesis, the relationship of these cognitive functions to high-performance in elite sport and especially soccer was investigated in a meta-analysis with 18 independent effect sizes based on 1410 athletes, and four subsequent studies with 388 elite soccer players in total. The endeavor of the present thesis has been operationalized and categorized into the five domains: cognition-expertise, cognition-motor, cognition-cognition, cognition-success and cognition-training. In agreement with previous studies but also as a novel expansion of them, several important associations among the domains became evident. The cognition-expertise analysis showed a small to medium-sized superiority of elite and expert athletes, compared to non-elite and non-expert athletes with noticeable influences of the elite versus expert definition. This general cognitive superiority was further analyzed in the other cognition domains using soccer as an example for an elite team sport where meaningful but specific relationships of certain cognitive functions and motor skills are evident. Specifically, the cognition-motor domain shows that working memory has the most consistent connection to the maximal anaerobic parameter of sprint and soccer-specific activities with the ball (e.g. dribbling) with small to large effect sizes. Similarly, cognitive flexibility is small to moderately related to the maximal anaerobic parameters of sprint and drop jump performance, both across all age groups under consideration (12-34 years of age). These cognition-motor associations are accompanied by cognition-cognition relations as evident in the small to moderately sized relationship between working memory, cognitive flexibility and coach-rated game intelligence also across all tested age groups. Furthermore, the cognition-success analysis found small to large relationships of all executive functions except for inhibition with game time along with the physical skills sprint and repeated intense exercise ability. Contrary, effect sizes of the relation to injury incidences are negligibly small apart from sprint and general endurance performance.

Consequently, the cognition-training domain aimed to evaluate training effects of the cognitive functions related to important aspects of all four domains. A multiple-object tracking tool was used for this and showed large task-specific and near-transfer effects to the trained skill but negligibly small further-transfer effects on other visual and executive functions. Implications of the findings for theory as well as for practice in sport are discussed.

The overall goal of this thesis is to shed light on the mechanisms by which cognitive functions are connected to high-performance in sport, especially soccer. Both previous, as well as the present studies, show the crucial relevance of certain cognitive functions in all performance domains altogether hinting at a key role of the central nervous system in steering and controlling performance in all areas.

# Abstract (German)

Bei der Untersuchung von Hochleistungs-Umfelder wird analysiert, welche Eigenschaften die Besten zu den Besten machen. Eines dieser Umfelder ist der Spitzensport, der eine der größten Herausforderungen für das menschliche Gehirn darstellt, da er eine Reihe von vielschichtigen Aspekten wie die Informationsverarbeitung der kognitiven Funktionen erfordert. In dieser Thesis wurde der Zusammenhang zwischen diesen kognitiven Funktionen und der Leistungsfähigkeit im Spitzensport und insbesondere im Fußball in einer Meta-Analyse mit 18 unabhängigen Effektgrößen auf der Basis von 1410 Athleten und vier Folgestudien mit insgesamt 388 Elite-Fußballern untersucht. Das Bestreben der vorliegenden Arbeit wurde operationalisiert und in die fünf Domänen Kognition-Expertise, Kognition-Motorik, Kognition-Kognition, Kognition-Erfolg und Kognition-Training eingeteilt. In Übereinstimmung mit früheren Studien, aber auch als neuartige Erweiterung dieser Studien, wurden mehrere wichtige Zusammenhänge zwischen den Bereichen deutlich. Die Analyse der Kognitionsexpertise zeigte eine kleine bis mittlere Überlegenheit von Elite- und Expertensportlern im Vergleich zu Nicht-Elite- und Nicht-Expertensportlern mit deutlichen Einflüssen der Definition Elite versus Experte. Diese allgemeine kognitive Überlegenheit wurde in den anderen kognitiven Bereichen weiter analysiert, wobei Fußball als Beispiel für eine Elite-Mannschaftssportart untersucht wurde, in der bedeutsame, aber spezifische Beziehungen zwischen bestimmten kognitiven Funktionen und motorischen Fähigkeiten herausgestellt wurden. Insbesondere der kognitiv-motorische Bereich zeigt, dass das Arbeitsgedächtnis die konsistenteste Verbindung zum maximalen anaeroben Parameter des Sprints und zu fußballspezifischen Aktivitäten mit dem Ball (z. B. Dribbeln) mit kleinen bis großen Effektstärken aufweist. In ähnlicher Weise steht die kognitive Flexibilität im kleinen bis moderaten Zusammenhang mit den maximalen anaeroben Parametern der Sprint- und Sprungleistung, und zwar in allen untersuchten Altersgruppen (12-34 Jahre). Diese Assoziationen zwischen Kognition und Motorik werden von Beziehungen zwischen Kognition (objektiv) und Kognition (subjektiv) erweitert, wie die kleine bis moderate Beziehung zwischen Arbeitsgedächtnis, kognitiver Flexibilität und von Trainern bewerteter Spielintelligenz, ebenfalls in allen untersuchten Altersgruppen zeigt. Darüber hinaus zeigte die Kognitions-Erfolgs-Analyse kleine bis große Zusammenhänge zwischen allen exekutiven Funktionen mit Ausnahme der Inhibition und der Spielzeit sowie den körperlichen Fähigkeiten Sprint und wiederholte intensive Belastungsfähigkeit. Im Gegensatz dazu sind die Effektstärken des

Zusammenhangs mit der Verletzungsinzidenz vernachlässigbar klein, abgesehen von der Sprint- und der allgemeinen Ausdauerleistung.

Folglich zielte der Bereich Kognitions-Training darauf ab, die Trainingseffekte der kognitiven Funktionen in Bezug auf wichtige Aspekte aller vier Bereiche zu analysieren. Hierfür wurde ein Multiple-Object-Tracking-Tool eingesetzt, das große aufgabenspezifische und Nah-Transfereffekte auf die trainierte Fähigkeit, aber vernachlässigbar kleine Entfernte-Transfereffekte auf andere visuelle und exekutive Funktionen zeigte. Die Ergebnisse werden sowohl für die Theorie als auch für die Praxis im Sport diskutiert.

Das übergeordnete Ziel dieser Arbeit ist es, Wissen über die Mechanismen zu generieren, durch die kognitive Funktionen mit Höchstleistungen im Sport, insbesondere im Fußball, verbunden sind. Sowohl frühere als auch die vorliegenden Studien zeigen die entscheidende Bedeutung bestimmter kognitiver Funktionen in allen Leistungsbereichen, was insgesamt auf eine Schlüsselrolle des zentralen Nervensystems bei der Steuerung und Kontrolle der Leistung in allen Bereichen hindeutet.

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# 1 Introduction

The functionalities and capabilities of the human brain are highly complex and the brain is said to be the most sophisticated system in the known universe (Ransford, 2015; Ebbage, 2020). Some of these capabilities are the cognitive functions which is a general concept referring to mental activities like knowledge acquisition, information manipulation, and reasoning containing the areas of perception, memory, learning, attention, decision making, and language skills (Kiely, 2014). It has been argued that these cognitive functions have primarily evolved to serve and enable the execution of motor functions which increased in complexity during human evolution (Leisman et al., 2016). However, our environment does not only demand that cognitive functions are used to enable optimal motor functioning but also that they are employed in perceiving and processing the complex stream of information emanating from our surroundings. At this point even the sophisticated cognitive system has its limitations in terms of handling all the information in complex situations (Marois & Ivanoff, 2005; Cohen et al., 2015). As Adam Gazzaley and Larry Rosen wrote in their book “The distracted mind”:

“We are ancient brains in a high-tech world” (2016, p. xv, prologue)

In previous centuries research examined the lower limits and abnormalities of these cognitive functions in case studies of neuropsychological patients who suffered severe brain damage to study the general anatomy and mode of action of the brain and its cognition (Damásio et al., 1994). By contrast, another line of inquiry emerged in the last decades which investigates the upper limits, achievements and possibilities of the brain and its cognitive functions by analyzing human high-performance across several domains to answer the question: “what makes the best the best?” (Walsh, 2014, p. 2). Thus, studying the abnormal but in this instance concerning the upper limits and outliers (i.e. elites) may gain insights that are equally important as are those produced by the previous approach.

Concerning these high-performance areas, elite sports represents one of the biggest challenges for the human brain as it demands a range of multifaceted aspects (Dietrich, 2006; Walsh, 2014). The quantity of information, the dynamics and openness of the game along with the time-pressure in elite sports require rigorous high-performance of athletes’ brains and their cognitive functions (Araújo et al., 2006; Davids & Araújo, 2010).

Imagine a game situation in a team sport like soccer where a player is dribbling with the ball. The demands on his brain are enormous: first he needs to execute complex and dynamic movements (i.e. dribbling) while simultaneously perceiving highly complex and dynamic visual and auditory stimuli with variable player positions and commands (moving teammates and opponents with high visual contrast and speed), variable surface composition and unanticipated perturbations. Furthermore, all this needs to be processed in milliseconds and matched with the tactical strategy to plan the next movement and make a fast decision to interact successfully with the environment (Grooms et al., 2015). When further considering that this is only one action which is delivered manifold in the 90 minutes of a soccer game where the performance level of the cognitive functions is also influenced by factors like mental fatigue (Smith et al., 2018) and psychological pressure, it becomes obvious that the cognitive performance of elite athletes is truly remarkable. It seems difficult to imagine that this game dynamic may become even more extreme. But this has happened: game speed increased by 15% and passing rate by 35% accompanied by a higher player density in soccer world cup finals from 1966-2010 (Wallace & Norton, 2014) consequently placing even higher loads on the cognitive functions.

Nevertheless, investigations at the junction of sport-science, cognitive neuroscience, and sport-psychology are just beginning to understand the relation of cognitive activities to athletic high-performance (Walsh, 2014; Yarrow et al., 2009b). Consequently, enlarging our understanding of how cognitive functions are associated with success of elite athletes and how they facilitate them to achieve high-performance is a crucial endeavor not only for the elite sport domain but also for the normal population as these insights can inform about underlying mechanism and principles of the brain's cognitive system. Thus, by understanding these mechanisms one might be able to make optimal use of- and enhance them for important situations in life.

In this first chapter I also want to clarify and define important terms frequently used throughout the thesis:

*Perceptual-cognitive skills* are defined as the skills of identifying and perceiving information from the environment. Subsequently, this information is combined with the present knowledge and facilitates the choice and completion of suitable reactions. The perceptual–cognitive skills allow the athlete to perceive the environment and to use this perception to generate an ideal decision for the subsequent action, which has a direct impact on the match result in team sports (Roca et al., 2013).

*Executive functions* are an important subclass among these perceptual-cognitive skills and refer to cognitive activities regulating thoughts and behaviors, particularly in non-routine conditions (Friedman et al., 2006). They are sectioned into core executive functions on the one hand and higher-level executive functions on the other hand. The former include working memory, cognitive flexibility and inhibition whereas the latter involve reasoning, problem solving, and planning – sometimes called metacognition (Diamond, 2013).

## 1.1 Aims of the thesis

The aim of this thesis is to analyze the underlying mechanisms of cognitive functions in high-performance team sports with a special focus on executive functions and elite soccer. A lot of research has already been done especially in the last years but several important questions still need to be answered. I seek to fill some of these gaps with my own experimental data. Additionally, I will also review and merge previous literature as well as include my own results into a more holistic understanding regarding executive functions in elite soccer.

Two important functions are addressed by exploring and comprehending the role of cognitive functions in high-performance sports. Firstly, studies like this can expand basic research as studying the abnormal (i.e. the elite) may offer crucial insights for the general population. Similar to neuropsychological single patient data which were used over a century ago as instructive case studies, these elite athletes representing population-outliers may be the new instructive case studies (Walsh, 2014). Specifically, learning more about the cognitive functions of these outliers and how they utilize them in a multidisciplinary high-performance setting may enable us to make useful generalizations. Additionally, resolving the interplay of cognitive and physical skills could inform us about underlying governing neural mechanisms of athletic peak performance which becomes even more important in the light of physical factors' relevance in modern sports (Jamil et al., 2021; Klemp et al., 2021; Low et al., 2021). Identifying the contributors to success and injury-absence in high-performance sport can also be instructive to understand how the brain is able to achieve extraordinary accomplishments like performing in elite sport situations (Walsh, 2014).

Secondly, gaining more knowledge of cognitive functions in elite sports can have valuable practical implications as well. For example, training programs may be adapted to the principles of the interplay between the cognitive and the physical skills and to potential key parameters which contribute to success and make it more efficient and holistic. Such a holistic approach may also be beneficial in the analysis of physical performance data. Our understanding of a player’s performance might be increased when we also consider the cognitive functions which could finally result in performance-increasing options. Those training options aiming to enhance cognitive performance are required to be evidence-based. Thus evaluating levels of transfer of distinct training tools is crucial for the progress of performance improvements.

My research on the cognitive functions in elite athletes and especially soccer is organized according to five main research aims. Every aim has the overall goal to inform about underlying mechanisms of the association of cognitive functions with high-performance, however each aim does that from different perspectives which are outlined in the following. The different domains refer to the cognitive differences between experts and elite performers in sports (i.e. cognition-expertise domain), the interplay of cognitive functions with motor as well as physical skills (cognition-motor domain), the relationship between cognition and game intelligence (cognition-cognition domain), the identification of certain cognitive functions and physical skills that contribute to success and absence of injury (cognition-success domain) and lastly to the investigation of transfer effects of a cognitive training tool (i.e. cognition-training domain).

The first aim is approached by applying the method of first principle thinking. In particular, one needs to evaluate at the outset to which extent experts and elite athletes differ in their cognitive performance in the first place. This is a necessary inquiry before investigating a certain type of sport in more detail. This analysis seeks to clarify currently conflicting findings on the diagnostics of cognitive functions in elite athletes and experts compared to amateurs whilst disentangling the influence of age, skill definition and different cognitive functions. Following this broad overview of the *cognition-expertise domain* the subsequent steps focus on the relationship of cognitive functions with important elements of a specific type of sport (i.e. soccer). The following three aims examine the *cognition-motor domain* and *cognition-cognition domain* in elite soccer players. A further objective is the investigation of the influence of distinct age groups on these interplays. The fourth aim is to analyse the *cognition-success domain* across different age groups. The last aim is to investigate transfer effects of a certain cognitive training tool to visual and executive functions after an intervention period and the possible prediction of training gains grounded on baseline performance.

## 1.2 Approach and outline of the synopsis

The synopsis of the present cumulative dissertation includes five manuscripts that all have been published in international peer-reviewed journals (see Table 1). Altogether, these five manuscripts include data from 4 studies with 388 participants as well as a meta-analysis summarizing 18 effect sizes and 1410 participants.

Table 1: *Publications included in the synopsis*

I. **Scharfen, H. E.**, & Memmert, D. (2019). Measurement of cognitive functions in experts and elite athletes: A meta-analytic review. *Applied Cognitive Psychology*. (Q1, Impact Factor: 1.71)
II. **Scharfen, H. E.**, & Memmert, D. (2019). The Relationship Between Cognitive Functions and Sport-Specific Motor Skills in Elite Youth Soccer Players. *Frontiers in Psychology*, *10*, 817. (Q2, Impact Factor: 2.78)
III. **Scharfen, H. E.**, & Memmert, D. (2021). The relationship of executive functions and physical abilities in elite soccer players. *German Journal of Exercise and Sport Research.* (Q2, Impact Factor: 1.41)
IV. **Scharfen, H. E.**, & Memmert, D. (2021). Fundamental relationships of executive functions and physiological abilities with game intelligence, game time and injuries in elite soccer players. *Applied Cognitive Psychology*. (Q1, Impact Factor: 1.71)
V. **Scharfen, H. E.**, & Memmert, D. (2021). Cognitive training in elite soccer players: evidence of narrow, but not broad transfer to visual and executive function. *German Journal of Exercise and Sport Research*, *51*(2), 135–145. (Q2, Impact Factor: 1.41)

Chapter 2 introduces research on cognitive functions. Specifically, section 1 discusses the main concepts and models while section 2 elaborates on the relevance for elite team sports with a special focus on soccer.

This synopsis aims to discuss the findings of my own studies in the light of previous literature to consequently enlarge the knowledge on underlying mechanisms of cognitive functions and their relation to elite athletes' performance. By using different perspectives on this topic used in the different studies of my own I seek to create a more holistic model on how cognitive functions relate to high-performance in sports and especially in soccer. Thus, chapter 3 focuses on this relation of cognitive functions to high-performance in elite athletes. The first section is devoted to the relation of cognitive functions with expertise and skill level investigated in *Publication I* (*cognition-expertise domain*). The second section examines this relation to important aspects with a special focus on elite soccer. Specifically, *Publication II* and *Publication III* investigate this association in terms of motor and physical skills (*cognition-motor domain*) whereas *Publication IV* analyzes the association with game intelligence (*cognition-cognition domain*). Further, the relationships with success (i.e. game time) and a prerequisite for it (i.e. injury absence) are examined in *Publication IV* (*cognition-success domain*). Subsequently, Chapter 3.3 with *Publication V* focuses on the training of cognitive functions in elite soccer players (*cognition-training domain*). As an overview, the four research questions addressed in this thesis along with the publications that contribute to answer these research questions are summarized in Table 2.

Finally, I will draw some general conclusions based on my own investigations and integrate them into a holistic framework of the relationship of cognitive functions with high-performance in elite athletes, especially soccer players. Furthermore, I will also discuss implications for practitioners and for research on cognitive functions in elite sport in general while outlining the limitations of my own studies and the whole research domain and recommending directions for future research.

Table 2: *Research questions addressed in this thesis along with relevant publications*

| Research Question | Relevant Publication |
|---|---|
| I. How do cognitive functions relate to expertise and skill level in high-performance athletes? (cognition-expertise domain) | |
| a. To what extent do domain-general cognitive functions differ among elite athletes/ experts and amateurs? | Meta-analytic aggregation of 18 effect sizes in *Publication I* |
| b. To what extent are skill definition, age and examined cognitive areas influencing this difference? | Meta-analytic aggregation of 18 effect sizes in *Publication I* |
| II. How do cognitive functions relate to motor and physical skills in elite soccer players? (cognition-motor domain) | |
| a. How large is the effect size of the relationship between cognitive functions and motor as well as physical skills in elite soccer players? | 2 studies in *Publication II and III* |
| b. To what extent is age influencing this relationship? | 1 study in *Publication III* |
| III. How do executive functions relate to success in elite soccer players? (cognition-cognition and cognition-success domain) | |

| | |
|---|---|
| a. How large are the effect sizes of the relationships between executive functions and game intelligence and the influence of age on it? | 1 study in *Publication II* |
| b. To what extent are executive functions (i.e. objective and coach-rated) and physiological skills related to game time and injury absence? | 1 study in *Publication IV* |
| c. To what extent are executive functions (i.e. objective and coach-rated) and physiological skills related to injury absence? | 1 study in *Publication IV* |
| d. To what extent is age influencing relationships of b) and c)? | 1 study in *Publication IV* |
| IV. To what extent does a multiple-object tracking training tool enhance the cognitive performance of elite soccer players? | |
| a. To what extent does near or far transfer to visual or executive functions occur? | 1 study in *Publication V* |
| b. To what extent does baseline performance relates to training gains? | 1 study in *Publication V* |

# 2 Cognitive functions – main concepts and practical relevance for elite sport

As this thesis focuses on cognitive functions it is important to get a general impression on their origins and the main concepts to fully comprehend the evidence and resulting discussion which is explored in the next chapters. To further establish the link to their relevance in elite sports I will also review the previous research with a special focus on soccer.

## 2.1 Main concepts

Research on cognitive functions in sports is divided into two approaches. Firstly, the expert-performance approach which examines the athletes' cognitive expertise by using sport-specific stimuli in sport-specific situations also referred to as ecological validity or domain-specificity (Mann et al., 2007; Starkes & Ericsson, 2003). Studies of this approach mainly analyzed aspects like eye movements, gaze behavior, anticipation, pattern recognition and decision-making (Aksum et al., 2021; Roca et al., 2013, 2021; Roca & Williams, 2016). Secondly, the cognitive component skills approach studying cognitive skills employing domain-general stimuli in domain-general contexts (i.e. sport-unspecific). This thesis belongs to the second approach as domain-general perceptual and cognitive skills are analyzed. Domain-general perceptual-cognitive skills are exemplary analyzed with the so-called attention window representing the attentional breadth and distribution which varies as a function of expertise and type of sports (Hüttermann et al., 2014; Hüttermann & Memmert, 2017).

Moreover, the executive functions are a crucial and particularly interesting subarea within the domain-general cognitive abilities and also represent the main focus of this thesis. These executive functions refer to the cognitive activities that control thought and action, particularly in non-routine situations (Friedman, 2006). They are further classified into two subcategories (Miyake et al., 2000; Diamond, 2013). Firstly, core-executive functions consisting of i) working memory: keeping information in mind and mentally working with it (e.g. information usage for problem-solving) (Garon et al., 2008). Simple working memory tasks only require temporal updates of certain information. Contrastingly, more complex tasks require directed manipulation and updating of information besides simple maintenance of information (Garon et al., 2008). A powerful working memory enables the individual to react to a completed task later in time, weigh up different alternative actions and relate information to each other (Diamond, 2013; Miyake et al., 2000a). Also, ii) cognitive flexibility: shifting ideas or perspectives to a problem and flexibly adapting to new demands or priorities (as in switching between tasks) (Diamond, 2013). Lastly iii) inhibition: controlling one's attention, behavior, thoughts, and/or emotions to overrule a strong internal predisposition or external lure (Diamond, 2013). By means of the ability of inhibition one is able to suppress irrelevant environmental stimuli and to focus on the relevant stimuli in order to accomplish the present task (Miyake et al., 2000; Diamond, 2013).

Secondly, higher-level executive functions including reasoning, problem solving and planning (sometimes referred to as "fluid intelligence" or "metacognition"). The prefrontal lobe is the main neural structure controlling the executive functions and matures slowly with reaching its full potential between the ages of 20 and 29 (De Luca, 2003 & Luciana et al., 2005). Contrastingly, brain areas like those responsible for sensory processing or attention develop earlier (Gogtay, et al., 2004; O'Hare & Sowell, 2008). Throughout this immaturity period progressive and regressive adaptations such as myelination and synaptic pruning take place. Additionally, these are partially driven by the individual's experiences (O'Hare & Sowell, 2008).

Chapter 2.2 will further describe demonstrations of executive functions in sport scenarios and especially emphasize the role executive functions can play in elite soccer.

## 2.2 Practical relevance for elite sport

Across the domains of human high-performance, elite sports is one of the biggest challenges for the brain as it requires a range of multifaceted activities and processes (Dietrich, 2006; Walsh, 2014) which makes it necessary for the athletes to adjust their behavior quickly and flexibly to the changing demands of the environment (Zelazo et al., 2003). Further, the amount of information, the dynamics and openness of the game combined with the time-pressure in elite sports demand rigorous high-performance of athletes' brains and their cognitive functions (Araújo et al., 2006; Davids & Araújo, 2010). Additionally, these game dynamics are still progressing as for example game speed increased about 15% and passing rate about 35% accompanied by a higher player density in soccer world cup finals from 1966-2010 (Wallace & Norton, 2014) resulting in even higher demands regarding the cognitive functions of the players.

One example for the possible relevance of cognitive functions in elite sports is the previously described working memory which is linked with several aspects of performance: perception and anticipation, choking under pressure, decision-making, imagery and skill acquisition/execution (Furley & Memmert, 2010). Furthermore, these demands on the brain and the importance of cognitive functions in elite sports are also underpinned by the current research. Firstly, it has been indicated that cognitive functions may help to discriminate elite athletes from nonelite athletes and athletes from nonathletes based on their current performance levels for example in volleyball (Formenti et al., 2019), soccer (Huijgen et al., 2015; Verburgh et al., 2014; Verburgh et al., 2016; Vestberg et al., 2020) and in a comparison of self- and externally paced sports (Jacobson & Matthaeus, 2014). Secondly, they also seem to be related to future success in tennis (Ishihara et al., 2019) and soccer (Sakamoto et al., 2018; Vestberg et al., 2020; Vestberg et al., 2012; Vestberg et al., 2017). Thirdly, it is suggested that cognitive functions are associated with essential aspects of elite sports like game intelligence (Vestberg et al., 2020). Consequently, the interest in training the cognitive performance level is very high. Some theoretical frameworks and neurocognitive adaptations of cognitive training (Constantinidis & Klingberg, 2016; Klingberg, 2016) and some practical findings for levels of transfer from cognitive training exist (Fleddermann et al., 2019; Parsons et al., 2016). However, evidence on cognitive training in elite athletes is scarce, shows conflicting results (Harenberg et al., 2021) and needs further evaluation (Walton et al., 2018). Furthermore, despite these promising findings on the importance of cognitive functions in elite sports, other studies do not confirm the generalization that better cognitive functions are associated with elite performance levels or expertise. This absence of differences is present among several levels of expertise in basketball (Furley & Memmert, 2010; Nakamoto & Mori, 2008) and ice hockey (Lundgren et al., 2016). Additionally, the previously mentioned studies reporting associations of better cognitive functions with better game performance or future success are very scarce and mostly preliminary based on small sample sizes. Consequently, there is a lack of agreement on the relevance of cognitive functions for example as a prognostic tool (Beavan et al., 2019; Beavan, Spielmann, et al., 2020).

# 3 Cognitive functions’ relation to high-performance in elite sports

This chapter addresses the multitude of associations of cognitive functions with high-performance in elite sports and especially soccer. Unravelling those associations sheds light on the underlying mechanisms and principles of the potential contribution of cognitive functions to high-performance. Thus, we attain a more holistic and comprehensive framework of those associations.

The relationship between cognitive functions and high-performance in elite sports can be investigated from three different angles and the present thesis allocates equal importance to all of them: the relationship of cognitive functions to 1) expertise and skill level by distinguishing the cognitive performance levels of experts and amateurs *(cognition-expertise domain)*, to 2) the essential aspects of a specific team sport – elite soccer – which are: 2a) motor and physical skills *(cognition-motor domain)*, 2b) game intelligence *(cognition-cognition domain)*, 2c) success (i.e. game time) and prerequisites for success (i.e. injury absence; *cognition-success domain)*. Lastly, angle 3) is devoted to the training and transfer of a certain cognitive skill *(cognition-training domain).*

All three angles will be further subdivided into separate topics. For each issue, previous research will be reviewed first and my own findings will be integrated afterwards to answer the respective research questions stated in chapter 1.2 above.

## 3.1 The relation of cognitive functions with expertise and skill level

This section provides an evaluation on the extent of the potential association of cognitive functions with expertise and skill level. The existing literature will be discussed in conjunction to my own research findings in terms of a meta-analytic review to give an answer to Research Question I. The rationale of this primary examination was to evaluate in a first step to what extent experts and elite athletes differ from non-experts and non-elite athletes in their cognitive performance. This is a necessary inquiry to better understand the cognition-expertise relation systematically before investigating a certain type of sport in more detail.

### 3.1.1 Previous research

In previous research studies predominantly focused on the expert performance approach (Starkes & Ericsson, 2003) by investigating athletes in ecologically valid or sport-specific situations (Aksum et al., 2021; Mann et al., 2007; Roca et al., 2021). A special emphasis was placed on the investigation of metrics quantifying the direct interaction of athletes with their specific environment. Thus, these studies mainly examined gaze behavior, eye movements, anticipation, declarative memory, attention and its allocation and decision-making by using sport-specific stimuli concerning differences of experts and novices (Scharfen & Memmert, 2019). The main result lies in determining the superiority of experts compared to nonexperts in the perception and response to sport-specific cues which is proved by experts' superior response accuracy and response time (Abernethy, 1990; Helsen & Starkes, 1999; Mann et al., 2007; Wright et al., 1990). This superiority is partially based on the more efficient gaze behavior of experts as they use fewer eye fixation points but focus them for a longer time (Helsen & Starkes, 1999; Mann et al., 2007; Savelsbergh et al., 2002; van Maarseveen et al., 2018). However, the diagnosis of this superiority in perceptual actions is strongly influenced by the research paradigm, stimulus and type of sport (Mann et al., 2007). Taken together, the expert performance approach indicates a superiority of elite athletes in sport-specific cognitive functions.

To further evaluate this superiority, the meta-analysis in *Publication I* focuses on the domain-general (i.e. sport-unspecific) cognitive functions based on the mass of studies analyzing detailed aspects of the expert performance approach like gaze and visual search behavior. Studies belonging to the cognitive component skills approach investigate the domain-general functions by examining the interaction between standardized cognitive tests potentially relevant for the cognitive demands of skilled sports and sporting expertise (Nougier et al., 1989). This approach examines general cognitive functions like inhibition and working memory in contrast to the expert performance approach (Nougier et al., 1989; Voss et al., 2010). A common criticism regarding the component skills approach is the absence of situational complexities that produce extraordinary expert performance (Starkes & Ericsson, 2003). Nevertheless, this approach represents important parameters of general cognitive functions associated with skilled sports (Voss et al., 2010). A previous meta-analysis (Voss et al., 2010) stated a small to medium sized effect for high-performance athletes in domain-general cognitive functions. However, only lower-level skills like processing speed were included in the investigation, resulting in a call to examine higher-level cognitive skills like executive functions (Voss et al., 2010). The findings of subsequent studies are important though they have not yet been analyzed systematically yet. Other investigations also align with the recommendations of Furley & Memmert (2011) to examine potential moderator variables like training experience (Huijgen et al., 2015). However, investigations belonging to the cognitive component skills approach yielded conflicting results with some studies suggesting a cognitive superiority in elite and expert athletes (Huijgen et al., 2015; Verburgh et al., 2014; Verburgh et al., 2016; Vestberg et al., 2012) and other studies indicating no cognitive differences (Furley & Memmert, 2010; Heppe et al., 2016). Additionally, diverging definitions of skill level, the difference in the cognitive tests applied and the age groups which were included also contribute to the fact that the present literature does not give a clear picture. Therefore, the following research questions are appropriate:

*Ia)* To what extent do domain-general cognitive functions differ among elite athletes/ experts and amateurs?

*Ib)* To what extent are skill definition, age and examined cognitive areas influencing this difference?

### 3.1.2 Answer to research question Ia and Ib

My own research intends to fill some existing gaps in this line of research. I shall first outline the results of my own investigation and then connect these to previous research in order to gain a better understanding of the difference in domain-general cognitive functions among elite/ expert and non-elite/ non-expert athletes.

*Publication I* aims to disentangle the various results in a meta-analysis both by presenting and interpreting previous research studies and by considering the new investigations which analyze executive functions. The cognitive component skills approach was used by investigating domain-general cognitive functions to examine general disparities in cognitive functions across certain types of sport with the exclusion of their individual sport-specific influences. Another aim was to analyze to what extent age, skill definition and the cognitive tasks which were used influence the potential disparities in cognitive functions across various sports regardless of individual categories (e.g. interceptive or strategic). A further aim of this study was to provide an overview of the cognitive functions and their specifically explored subareas. Across the filtered studies, 18 independent samples existed, leading to 18 independent effect sizes based on a sample size of 1,410 individuals in total.

Considering all studies under review, a small to medium sized effect (*r* = 0.22) was found in the meta-analysis (see *Publication I*) indicating a noticeable superiority of domain-general cognitive functions in elite and expert athletes compared to low-performance athletes (see Figure 1). This is in contrast to the heterogenic results in the individual studies. This finding is in accordance with the cognitive superiority of high-performance athletes in meta-analyses examining studies of the i) expert performance approach by Mann et al. (2007) and ii) cognitive component skills approach by Voss et al. (2010). More importantly, these findings are even expanded by the current results as they add the superiority of executive functions in elite and expert athletes. However, the cognitive subarea of executive functions does not represent this superior effect in total although most of the studies depict small to medium sized effects (see Figure 2). This may stem from certain studies investigating this subarea - group athletes by using the category of an “expert athlete” instead of an “elite athlete” definition. The first definition is based on the training time aggregated over years (Ericsson et al., 1993) whereas the second classifies the athletes based on their current competition level or the division in which they recently compete (Swann et al., 2015)

This difference probably influences the results because the “elite” definition leads to a significantly greater effect size. Thus, discriminating athletes based on their aggregated training experience as proposed by Ericsson et al. (1993) is probably not exact enough to discriminate top-performance and semiprofessional athletes. The underlying issue is the great variance concerning the training quality which strongly differs from athlete to athlete as suggested by the theory of deliberate practice (Macnamara et al., 2016). On the other hand, the categorization of high-performance athletes grounded on their actual competition level or the division in which they are currently playing at least excludes the probability of incorrectly allocating athletes to the high-performance group. However, this approach is not absolutely valid either as some athletes from division 2 may also have the abilities to perform in division 1 or the other way around. Consequently, future studies should classify high-performance athletes by using the elite instead of the expert categorization.

Furthermore, the influence of age on the results was not statistically significant. There is a high probability that the cognitive superiority of high-performance athletes is not constrained to single cognitive functions but rather includes most of them as certain cognitive functions and their associated brain structures mature at different developmental phases but no difference was evident between age groups. As the first of its kind *Publication I* analyzed this difference among age groups.

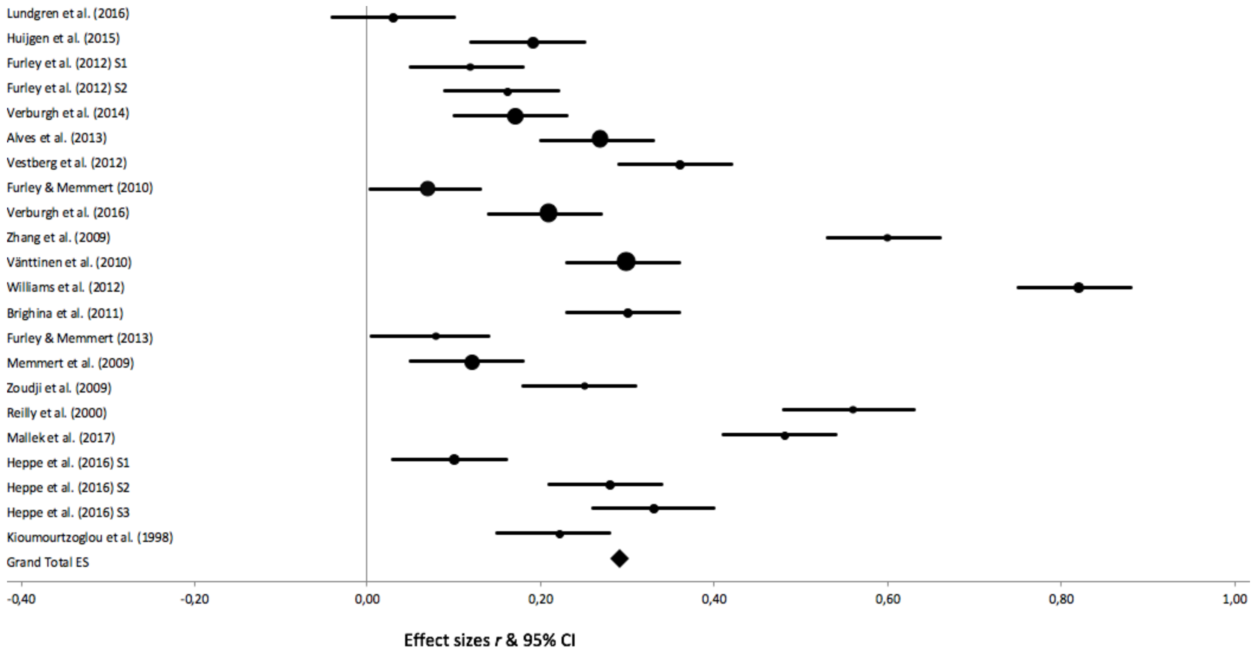

*Figure 1.* Forest plot with effect sizes r and confidence intervals of each independent sample from *Publication I*. *Note:* the size of the middle point of each confidence interval represents the respective sample size of the individual study (from *Publication I*).

The third moderator variable – type of cognitive test – showed no meaningful influence on the results. This variable is represented by the different examined cognitive subareas i) executive functions, ii) visuo-perceptual functions, and iii) other cognitive functions. As most of the studies belonging to this subarea of executive functions discriminated elite from non-elite athletes (e.g. Huijgen et al., 2015; Verburgh et al., 2014; Vestberg et al., 2012) we believe that the assessments would have yielded more statistical power and thus would have been more conclusive if all studies had applied the elite definition along with larger sample sizes. Although different visuo-perceptual tests were used, the small to medium effect size of the visuo-perceptual functions represents the largest effect of the subareas and confirms results of the previous meta-analyses (Mann et al., 2007; Voss et al., 2010). The last subarea of other cognitive functions including a mixture of several aspects (e.g. decision-making, processing speed), represents the second largest effect.

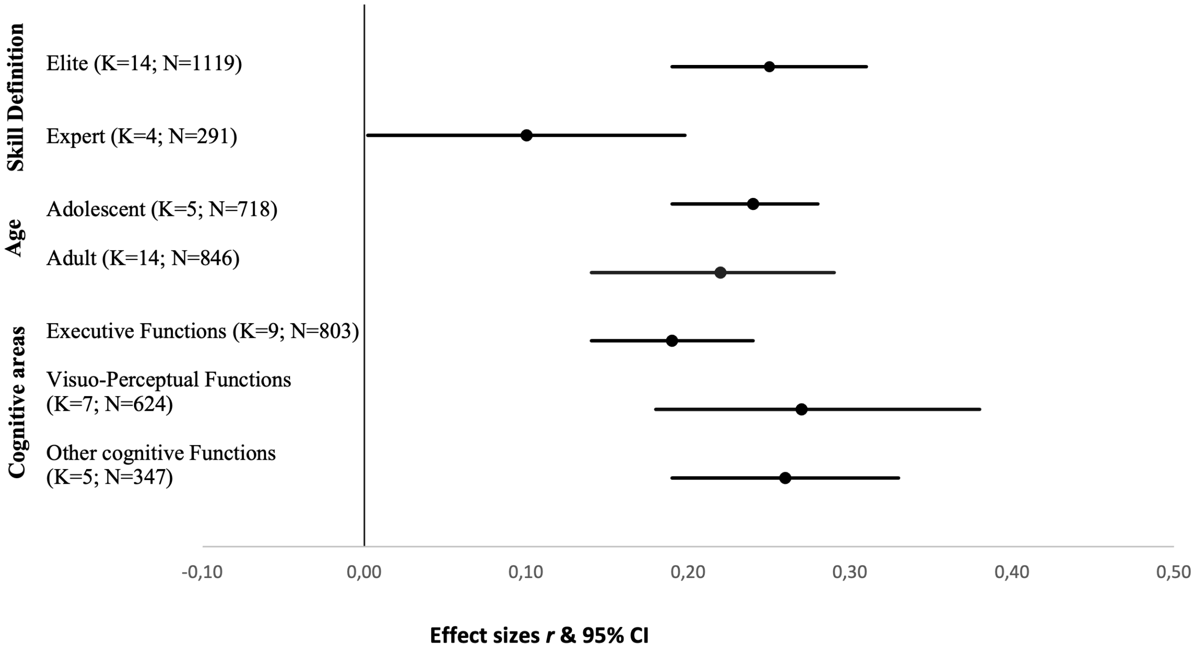

*Figure 2.* Effect sizes *r* and confidence intervals of moderator variables from *Publication I* (K= number of studies, *N*= number of participants) (from *Publication I*).

Summed up, research questions Ia and Ib can be answered as follows based on the findings of *Publication I:*

*Ia*: The extent to which elite/ expert athletes and non-elite/ non-expert athletes differ in their domain-general cognitive performance is small to medium sized (*r* = 0.22) favoring a superiority of elite/ expert athletes

*Ib*: The influence of skill definition on the difference in cognitive functions is small to medium sized as the “elite” definition yields a greater effect size compared to the “expert” definition (*r* = 0.25 vs 0.01). Secondly, the effect of age on the difference in cognitive functions is negligibly small (*r* = 0.24 vs 0.22, adolescents vs adults) similar to the influence of different cognitive areas.

## 3.2 The relationship of cognitive functions to important aspects of elite soccer

The results of applying a first principle method as shown in *Publication I* (see Chapter 3.1), indicate that elite athletes have superior cognitive functions compared to non-elite athletes. In this context the subcategory of executive functions depicts an especially promising contributor to this cognitive advantage. Therefore, after assessing this general cognitive superiority across several types of sport the subsequent question arises how this advantage is converted into high-performance of a certain sport type. This is where soccer comes into play as this line of research has been indicated to be a fruitful endeavor by a multitude of studies (Huijgen et al., 2015; Verburgh et al., 2014; Verburgh et al., 2016; Vestberg et al., 2020; Vestberg et al., 2012; Vestberg et al., 2017). One might add that soccer also causes a high collective attention as it is a ubiquitous sport participated in by 265 million players worldwide (FIFA, 2013). Furthermore, the characteristic requirements for a successful soccer player represent a multidimensional combination of physical and cognitive aspects (Huijgen et al., 2015; Klemp et al., 2021; Low et al., 2021; Murr, Feichtinger, et al., 2018; Murr, Raabe, et al., 2018; Verburgh et al., 2016)

Thus, informed by the findings of *Publication I* (see Chapter 3.1), a special focus of the subsequent studies of *Publication II, III IV and V* was placed on the executive functions and their relation to important aspects of performance in elite soccer players. Consequently, this section 3.2 provides an evaluation of the possible association of executive functions with important aspects in elite soccer players.

The existing literature will be discussed in conjunction with my own research findings in terms of two studies from *Publication II, III and IV* to answer to Research Questions II and III. The association of executive functions with important aspects of elite soccer will be investigated from four different angles to analyze four different aspects. Firstly, motor and physical skills are focused on in two studies in *Publication II and III* (cognition-motor domain), secondly game intelligence (cognition-cognition domain), thirdly success (i.e. game time), and fourthly, the prerequisites for success (i.e. injury absence, cognition-success domain) are all analyzed in one study in *Publication IV.*

### 3.2.1 The relationship of cognitive functions with motor and physical skills in elite soccer players

As part of the paramount question how the cognitive superiority of elite athletes is converted into high-performance, this first line of inquiry evaluates the possible association of cognitive functions with a special focus on executive functions with motor and physical skills in elite soccer players. The existing literature will be discussed in conjunction to my own research findings in terms of two studies from *Publication II and III* to answer to Research Question II in this paragraph.

### *3.2.1.1 Previous research*

Some of the multifaceted neural demands of elite sports rest on the cognitive- and especially on the executive functions which have been shown to be crucial for success in team sports (Scharfen & Memmert, 2019; Voss et al., 2010); a multitude of studies were done with reference to soccer. The brain is also required to decide on and control precise motor actions and physical skills which are crucial elements of soccer and other team sports (Abade et al., 2014; Klemp et al., 2021; Murr, Raabe, et al., 2018). Taken together, elite team sport represents one of the most demanding activities for the brain by demanding a range of multivarious aspects in combination (Dietrich, 2006; Walsh, 2014). Therefore, examining this multivarious peak performance may also yield insights into high-performance of the general population (Walsh, 2014) especially as youth athletes are also already high-performers although their brains and bodies of are not fully developed yet (Luca et al., 2003; Luciana et al., 2005). Thus, by integrating several age groups in *Publication II* and *III* it may be explored for the first time if fundamental cognition-motor connections for athletic expertise are present across various phases of development. However, science at the junction of sport science, sport psychology and cognitive neuroscience is only just beginning to comprehend the cooperation of neural and cognitive activities with physical processes needed to facilitate peak performance (Huang et al., 2017; Yarrow et al., 2009). This preliminary line of research primarily explored theoretical frameworks like the neural interconnections of pathways linked to cognitive and motor activities (Gao et al., 2018; Leisman et al., 2016), whereas the behavioral data underlying these interconnections and the influence of different developmental phases on these processes are very rare. Thus, so far no study has examined elite soccer players of different age groups regarding their comprehensive mixture of cognitive and motor performance yet. Consequently, the examinations of *Publication II and III* are innovative by expanding the initial research on the interconnection of the distinct disciplines among certain age groups. These theoretical frameworks explain the cognition-motor connection with its underlying neural basis represented by similarities in functional brain networks. Further it is proposed that the evolutionary purpose of working memory and other executive functions are the support of precise control of motor actions and that of attention is the facilitation of optimal motor activities (for review see Leisman et al., 2016). This similarity is also underlined by the shared resources of structural brain networks as a neural network consisting of the cerebellum, frontal lobe and basal ganglia cooperate with each other to control intentional movements and cognitive functions (Gao et al., 2018; Leisman et al., 2016). The model of neural efficiency further suggests an association of sophisticated cognitive performance with more efficient neural activities representing lower energy demands (Leisman et al., 2016). The underlying principle is the brain's desire to use the minimal possible energy amount based on its boundedness of energetic reserves causing a rivalry of neural activities (Dietrich, 2006). By combining this energetic boundedness with the shared cognition-motor networks the notion appears that more efficient cognitive activities liberate neural processing capacities accompanied by more energy usable for planning and execution of motor activities. Behavioral evidence on this linkage of sophisticated cognitive skills with sophisticated motor skills are present in young children (Gottwald et al., 2016; Jansen & Heil, 2010; Lehmann et al., 2014; Van Der Fels et al., 2015). Nevertheless, the examination of particular processes and interactions of distinct motor and cognitive skills is required to complement this general linkage. Therefore, the analyses of *Publications II* and *III* targets the linkage of both domains by investigating skills with a direct relation to sporting success in high-performance athletes.

Moreover, physical activity has also been shown to improve cognitive skills by means of cellular, structural and behavioral adaptations (Ludyga et al., 2020; Stillman et al., 2016) accompanied by moderator variables like motor expertise (Voyer & Jansen, 2017). Taken together this leads to the research questions:

*IIa:* How large is the effect size of the relationship between cognitive functions and motor as well as physical skills in elite soccer players?

*IIb:* To what extent is age influencing this relationship?

### *3.2.1.2 Answer to research question IIa and IIb*

My findings will be outlined and subsequently incorporated into the previous results to yield a comprehensive image on the cognition-motor relationship. *Publication II* investigates the possible cognition-motor relationship by studying 15 youth elite soccer players of 11-13 years of age in a preliminary analysis; and 172 youth and adult elite soccer players of 12-34 years of age were studied in *Publication III.* Another aim was to examine to what extent the factor age influences the cognition-motor association (*Publication III)* examined by integrating numerous age groups. Consequently the extent of fundamental associations for athletic expertise (here represented by soccer) across distinct age groups may be examined.

Taken together, the results of *Publication II* and *III* indicates that several cognition-motor relationships exist, however both domains are linked together in a very specific way rather than generally. Firstly, *Publication II* provides several main findings. In particular, a wider diagonal attention window representing the individual attention breadth is positively linked with more precise and faster soccer dribbling skills (see table 3). This may be based on the perception of more visual information in a player's attention window potentially resulting in the execution of early reactions of their sensorimotor processes to enhance the efficiency of their performance. This could be advantageous in game situations where the player dribbles while focusing on the ball, his opponents and teammates probably resulting in avoiding opponent contact and dribbling towards spaces already occupied by teammates.
Further, working memory capacity representing one of the core executive functions shows meaningful correlations with ball juggling, ball control, dribbling and a total motor score in accordance with the superiority of cognitive skills (as seen in *Publication I* and similar previous findings; Vestberg et al., 2012; Voss et al., 2010). These working memory-motor linkages confirm prior results indicating an association with superior athletic performance, previous exposure to organized sports (Verburgh et al., 2014; Verburgh et al., 2016) and the suggestion that the evolutionary purpose of working memory is motor control (Leisman et al., 2016). Contrary to these positive relationships no linkages were found for multiple object tracking or perceptual load – testing the resistance to irrelevant distractors – with motor skills aligning with the null findings of cognition-motor relationships in other studies (Baláková et al., 2015; Furley & Memmert, 2010). However, the irrelevant effect size could as well originate in the different demands as none of the motor tests requires for example the multiple tracking of objects or players.

Table 3: *Correlations $r_s$ between cognitive and motor-technique tests (from Publication II)*

| | Speed (20 m) | Acceleration (10 m) | COD | Dribbling | Ball control | Ball-Juggling | Total Score |
|---|---|---|---|---|---|---|---|
| MAW diagonal | | | | | | | |
| Correlation coefficient | .087 | -.014 | .339 | .656** | .380 | .098 | .395 |
| Sig. (2- fold) | .758 | .961 | .216 | .008 | .162 | .729 | .145 |
| Effect size (d) | .175 | -.027 | .721 | 1.74 | .822 | .197 | .860 |
| MOT | | | | | | | |
| Correlation coefficient | -.047 | -.126 | -.032 | .125 | .146 | .123 | .175 |
| Sig. (2- fold) | .869 | .656 | .909 | .657 | .603 | .664 | .533 |
| Effect size (d) | -.093 | -.254 | -.064 | -.252 | -.294 | -.248 | .356 |
| PL high reaction time | | | | | | | |
| Correlation coefficient | -.029 | -.143 | .211 | .318 | .425 | .418 | .396 |
| Sig. (2- fold) | .919 | .610 | .449 | .248 | .114 | .121 | .143 |
| Effect size (d) | -.058 | -.289 | .432 | .671 | .939 | .921 | .863 |
| PL low reaction time | | | | | | | |
| Correlation coefficient | -.095 | -.056 | -.409 | -.396 | .075 | .168 | .021 |
| Sig. (2- fold) | .737 | .844 | .130 | .143 | .791 | .551 | .940 |
| Effect size (d) | -.191 | -.112 | -.895 | -.863 | .150 | .341 | .430 |
| WMC | | | | | | | |
| Correlation coefficient | -.260 | -.249 | .197 | .562* | .669** | .727** | .553* |
| Sig. (2-fold) | .350 | .371 | .480 | .029 | .006 | .002 | .033 |
| Effect size (d) | -.539 | -.513 | .402 | 1.39 | 1.81 | 2.12 | 1.33 |

| | Motor Total |
|---|---|
| Cognition Total | |
| Correlation coefficient | .614* |
| Effect size (d) | 1.56 |
| Sig. (2-fold) | .015 |

*The correlation is significant at .05 level (twofold); ** The correlation is significant at .01 level (twofold);

*Note.* For all measurements, the number of participants was equal ($n$ = 15). COD=change of direction, AW= attention window, MOT= multiple object tracking, PL= perceptual load, WMC= working memory capacity

Although, some investigations considered with the perception-action coupling approach (Davids et al., 2013; Pinder et al., 2009; Renshaw & Davids, 2004) provide evidence on the importance of perception for performance these findings from *Publication II* are among the first stating a positive linkage of a cumulated score of all generic cognitive and motor tasks, indicating a fundamental cognition-motor interrelation.

*Publication III* shows various cognition-motor correlations which are not general but rather very specific as well indicating the absence of a one-fits-all explanation (see table 4). Specifically, the non-meaningful trend in the correlation of working memory and acceleration/sprint seen in *Publication II* is expanded into small to moderate, meaningful correlations in *Publication III,* which could be an effect of the bigger sample size. The results generally indicate that anaerobic compared to endurance parameters are more closely related to cognitive skills. Cognitive flexibility and working memory represent the most stable relations to maximal anaerobic measures of jump and sprint expanding the preliminary findings on working memory from *Publication II*.

However, it is even more essential to examine the relations to specific areas of physical performance.

Regarding the relation of endurance abilities and executive functions, only the repeated intense exercise ability is small to moderately correlated with inhibition indicating a weaker endurance performance in players with better inhibitory skills. In opposition to this finding previous results suggest that cognitive processes are more strongly related to self-determination of the maximal performance stage as inherent in the repeated intense exercise ability (Blanchfield et al., 2014). However, the absolute capabilities of endurance performance do not automatically represent the adequate and efficient usage of these capabilities concerning optimal running paths in situations of the game. The study of *Publication III* analyzed the subarea “response inhibition” described as inhibition of behavior (Diamond, 2013), which makes it imaginable that players capable of better response inhibition apply their endurance capabilities in a more efficient way since they may be capable of inhibiting avoidable running paths. Thus, the resulting decreased workload would lead to weaker endurance capabilities (Malone et al., 2019).

Moreover, this negative correlation of inhibition and repeated intense exercise ability was largely influenced by the moderator variable age probably confirming similar findings of previous research since both skills develop with increasing age (Beavan, Chin, et al., 2020; Ford et al., 2011). However, no other meaningful correlations were present which may be due to the comparably small variances in this relatively homogeneous elite athlete population.

In terms of maximal anaerobic performance, a meaningful correlation was present for linear sprint with working memory, cognitive flexibility and the combined value of all cognitive skills whereas age had no moderating influence on this relation. This association aligns with the proposed evolutionary purpose of working memory to control motor actions (Leisman et al., 2016). Thus, as sprint is among the physical activities with peak demands on the neuromuscular system concerning intensity and load (Malone et al., 2018), a sophisticated working memory capacity may consequently lead to sophisticated neuromuscular coordination resulting in better sprint performance.

Additionally, the very fast changes of extremely different motor patterns may explain the association of cognitive flexibility with better sprint performance. Particularly, the change from standing still to a sudden sprint with maximal velocity represents extremely high neuromuscular intensities and loads (Malone et al., 2018). Moreover, the starting phase of the sprint seems to demand more attentional resources to initiate the start of the explosive and complex neuromuscular coordination while the explosivity decreases with heightened running speed and distance (Bezodis et al., 2019), since the correlations of working memory and cognitive flexibility are larger with the 10-meter than with the 30-meter sprint time. Crucially, these associations appear to exist among all developmental phases included in the study, since the age of the participants attenuated but did not meaningfully influence them. Thus, this finding represents an important new insight of previous knowledge as it proposes a fundamental association essential for athletic expertise at all ages.

Table 4*: Partial correlations between executive functions and physical abilities whilst controlling for age Group (from Publication III)*

| | Performance-IAT | Sprint (10m) | Sprint (30m) | SJ | CMJ | DJQ | RIEA |
|---|---|---|---|---|---|---|---|
| Working Memory | | | | | | | |
| Spearman's *r* | 0.09 | **-0.33** | **-0.24** | 0.17 | **0.19** | 0.11 | 0.20 |
| CI | -0.22, 0.37 | **-0.5, -0.15** | **-0.41, -0.05** | -0.10, 0.41 | **0.01, 0.40** | -0.07, 0.27 | -0.07, 0.44 |
| *n* | 42 | **103** | **103** | 56 | **122** | 122 | 56 |
| Cognitive Flexibility | | | | | | | |
| Spearman's *r* | 0.17 | **0.23** | **0.20** | 0.13 | -0.05 | **-0.27** | 0.11 |
| CI | -0.14, 0.45 | **0.04, 0.41** | **0.01, 0.38** | -0.14, 0.38 | -0.23, 0.13 | **-0.43, -0.10** | -0.16, 0.35 |
| *n* | 42 | **103** | **103** | 56 | 122 | **122** | 56 |
| Inhibition | | | | | | | |
| Spearman's *r* | 0.25 | -0.01 | **-0.23** | **0.55** | 0.09 | 0.10 | **0.28** |
| CI | -0.06, 0.51 | -0.20, 0.17 | **-0.41, -0.04** | **0.34, 0.71** | -0.09, 0.25 | -0.08, 0.26 | **0.02, 0.51** |
| *n* | 42 | 103 | **103** | **56** | 122 | 122 | **56** |
| Included teams | U16-U19 | U13-U23 | U13-U23 | U15-U19 | U13-first team | U13-first team | U14-U19 |
| MOT | | | | | | | |
| Spearman's *r* | 0.04 | 0.01 | -0.08 | 0.02 | 0.07 | -0.09 | 0.01 |
| CI | -0.27, 0.34 | -0.22, 0.24 | -0.31, 0.15 | -0.24, 0.28 | -0.14, 0.27 | -0.29, 0.12 | -0.28, 0.31 |
| *n* | 42 | 72 | 72 | 56 | 91 | 91 | 42 |
| Cognition Total | | | | | | | |
| Spearman's *r* | 0.04 | **-0.24** | -0.06 | 0.06 | 0.06 | 0.03 | 0.04 |
| CI | -0.27, 0.34 | **-0.45, -0.01** | -0.29, 0.17 | -0.21, 0.32 | -0.15, 0.26 | -0.18, 0.23 | -0.27, 0.34 |
| *n* | 42 | **72** | 72 | 56 | 91 | 91 | 42 |
| Included teams | U16-U19 | U15-U23 | U15-U23 | U15-U19 | U15-first team | U15-first team | U15-U19 |

*Note.* IAT: individual anaerobic threshold, SJ: squat jump, CMJ: counter-movement jump, DJQ: drop jump quotient, RIEA: ability to repeatedly perform intense exercises, MOT: multiple-object tracking; meaningful correlations are highlighted with bold numbers

The last aspect concerns the negative linkage of sprint (30-meter time) and inhibition which may also be grounded in the formerly proposed higher efficiency in the usage of physical capabilities leading to decreased workloads in players with sophisticated inhibition.

Nevertheless, the rationalization is rather hypothetical as this result has been shown for the first time.

The distinct linkages between vertical jump performance and executive functions are present for the first time as well. One of these jump parameters is the countermovement jump representing small to moderate correlations with working memory, again aligning with the proposed evolutionary core responsibility of working memory to steer motor movements (Leisman, 2016). Additionally, continuous training including this maximal anaerobic movement could also influence working memory in a bidirectional way.

This would support i) proposals stating a common and shared developmental source of cognitive and motor functions with the unifying purpose of motor action control (Gottwald et al., 2016; Van Der Fels et al., 2015) and ii) the benefits of physical specifically coordinative actions on cognitive functions (Ludyga et al., 2020). Again, the activity-dependent maturation of the central nervous system and musculature may contribute to the moderate influence of age on working memory's relationships with countermovement- and squat jump.

Furthermore, the linkage between cognitive flexibility and drop jump may be due to the comparable task demands. As cognitive flexibility describes being able to switch attention between strategies or task sets (Miyake et al., 2000b), a better performance of this ability may result in a better drop jump performance since that task requires an explosive and fast shift among two different motor sets or strategies (i.e. moving downwards vs jumping upwards) as well.

Finally, squat jump and inhibition are negatively linked suggesting that players with better inhibitory skills have poorer jumping performance. Playing at winger positions in soccer may require less inhibitory skills as the sideline reduces the number of directions and thus potentially the complexity of cognitive demands. Therefore, the tight relation of squat jump and sprint performance (Köklü et al., 2015) could contribute to this association as physically faster players may be placed at winger positions more frequently. However, no descriptive data are available for this hypothesis currently which makes it only speculative.

To summarize, findings from *Publication II* and *III* are generally in accordance with reciprocal influences of shared cognitive and motor networks in functional and structural dimensions (Bigelow & Agrawal, 2015; Darki & Klingberg, 2015; Gao et al., 2018; Hanakawa, 2011; Koziol et al., 2012; Leisman et al., 2016; Ptak et al., 2017), the beneficial effects of physical activity on cognition (Ludyga et al., 2020; Stillman et al., 2016) and behavioral data showing similar cognition-motor relations in nonathletic children (Gottwald et al., 2016; Jansen & Heil, 2010; Lehmann et al., 2014; Van Der Fels et al., 2015).

Taken together, research questions IIa and IIb can be answered as follows based on the findings of *Publication II* and *III:*

*IIa:* Meaningful but specific relationships of certain cognitive functions and motor skills are evident. Specifically, working memory shows the most consistent linkage to the maximal anaerobic parameter sprint and soccer-specific activities with ball (e.g. dribbling) with small to large effect sizes. Similarly, a small to moderate correlation is present among cognitive flexibility and the maximal anaerobic parameters sprint and drop jump performance.

*IIb:* No generalizing answer can be given as age does not commonly influence all but only specific cognition-motor relationships with small to large effect sizes. Some other associations – especially concerning working memory and cognitive flexibility linkages – are not substantially influenced by age indicating a fundamental relationship across several developmental phases.

### 3.2.2 The relationship of cognitive functions with game intelligence in elite soccer players

As outlined in Chapter 3.2.1 and in the results of the *Publications II* and *III* cognitive functions are associated with certain motor and physical skills. Therefore, it may be worthwhile to complement these findings on the cognition-motor domain with an investigation of the cognition-cognition domain. Specifically, by examining the relation of coach-rated game intelligence with cognitive functions. Again, the existing literature will be discussed in conjunction to my own research findings in terms of one study from *Publication IV* to answer to Research Question IIIa in this paragraph.

#### *3.2.2.1 Previous research*

Elite athletes use their so-called game intelligence to meet the cognitive demands of high-performance sports. Currently, no agreement for a common definition exists (Wein, 2004; Stratton et al., 2004), but professional coaches' notion of its elements, grades in athletes and crucial relevance for game success is generally strong and reliable. Previous research states the importance of executive functions in elite sports like soccer (Huijgen et al., 2015; Verburgh et al., 2014; Vestberg et al., 2012; Vestberg et al., 2017) by quantifying them with objective data. However, best practice recommendations suggest to incorporate coach-rated measures of cognitive performance like game intelligence as well, which has been scarcely applied before (Williams et al., 2020). One first study used the design fluency test which combines all three executive functions and shows a moderate correlation with coach-rated game intelligence in adult elite soccer players (Vestberg et al., 2020) whereas data of such an association in adolescents are currently non-existent. Therefore, a multiphasic investigation by examining various age groups could analyze the extent of the cognition-cognition interaction across several developmental phases for the first time. Such an investigation of possibly fundamental cognition-cognition relationships would i) provide a fruitful performance-needs analysis of actual demands in high-performance soccer and ii) contribute to an operationalization and a more holistic comprehension of the complex construct of game intelligence at several developmental stages. Thus, one line of investigation in *Publication IV* aims to analyze the connection of coach-rated game intelligence and objective diagnostics of executive functions with the specific research question:

*IIIa:* How large are the effect sizes of the relationships between executive functions and game intelligence and the influence of age?

#### *3.2.2.2 Answer to research question IIIa*

The results of *Publication IV* show a small to moderate correlation of game intelligence with the executive functions working memory and cognitive flexibility whereas inhibition and selective attention (multiple-object tracking) show no meaningful association (see table 5). The meaningful relations confirm the previous findings of Vestberg et al. (2020) while the effect size of the findings from *Publication IV* is marginally larger in comparison ($r$= 0.42 vs 0.37) possibly due to the doubled sample size. Crucially, the current findings represent this association in adults, adolescents and children for the first time across all developmental phases (i.e. from 12-34 years of age) since age did not meaningfully influenced the relation.

Thus, the preliminary results of adult players (Vestberg et al., 2020) are substantially extended by the present findings. In particular, the linkage of executive functions with game intelligence indicates an integral association essential for expertise in soccer in each examined age group. The suggestion of Vestberg et al. (2020) that particularly cognitive flexibility contributes to game intelligence aligns with the present findings. In contrast to the current results no linkage between game intelligence and working memory was present in the previous investigation (Vestberg et al., 2020); this may possibly be due to the different working memory tests which were used. Vestberg et al. (2020) applied different n-back tests which requires the player to respond if a presented card appears earlier in the test protocol. These tests are valid but may not be able to represent ecologically valid requirements of complex and quickly changing soccer games regarding the working memory system. Therefore, the counting span working memory test used in *Publication IV* makes use of randomly arranged, specific forms between distractors which the player needs to count while remembering the total counts for a subsequent recall. The exact order of the displayed counts need to be filled into a recall mask after two to seven image presentations. This version does not capture all complexities and dynamics of soccer as well but the overlapping demands are higher compared to the n-back tasks from my point of view.

Table 5*: Partial correlations between executive functions and game intelligence whilst controlling for age groups (from Publication IV)*

| | Selective Attention | Working Memory | Cognitive Flexibility | Inhibition | Cognition Score |
|---|---|---|---|---|---|
| Game intelligence | | | | | |
| Spearmans's *r* | 0.16 | **0.28** | **0.30** | 0.07 | **0.29** |
| CI | -0.02, 0.33 | **0.13, 0.42** | **0.15, 0.44** | -0.09, 0.22 | **0.12, 0.45** |
| *n* | 116 | **156** | **156** | 156 | **112** |
| Included teams | U15-first team | U13-first team | U13-first team | U13-first team | U15-first team |

Taken together, research question IIIa can be answered as follows based on the findings of *Publication IV:*

*IIIa:* The meaningful relationship between the executive functions working memory and cognitive flexibility and coach-rated game intelligence is small to moderate across all tested age groups (12-34 years of age).

### 3.2.3 The relationship of cognitive functions with game time and injuries in elite soccer players

As elaborated in the previous Chapters 3.2.1, 3.2.2 and the *Publications II, III* and *IV* executive functions show substantial and specific associations firstly with motor and physical skills (cognition-motor domain) and secondly with game intelligence (cognition-cognition domain). Taken together, these findings indicate a widespread connection of executive functions with essential aspects of soccer. Subsequently and based on as well as informed by these findings, the next examination heads towards the direction of identifying the contribution of even more important aspects of soccer, namely the ability to play – being free of injury – and the accumulation of game time which are two of the most important aspects of sustained, long-term high-performance (Rumbold et al., 2020). Therefore, the present section focuses on the investigation of the third branch, the relationship with success - measured by game time - and a prerequisite to success - measured by injury absence which altogether represent the cognition-success domain.

#### 3.2.3.1 Previous research

A first line of research analyzes which aspects account for success in high-performance environments like elite soccer. The identification of talent and aspects accounting for performance independently of age form an especially important part of those high-performance environments (Coulson-Thomas, 2012). As previous studies and Publications I and II (Huijgen et al., 2015; Scharfen & Memmert, 2019; Scharfen & Memmert, 2019; Verburgh et al., 2014; Verburgh et al., 2016; Vestberg et al., 2012; Vestberg et al., 2017) propose, domain-general cognitive and especially executive functions are among those aspects accounting for success. Therefore, there is great interest of soccer clubs and associations to identify players with certain cognitive characteristics which may support their current or later success on a professional level. However, it is still unknown to what extent a mixture of physiological along with objective and coach-rated cognitive skills account for success in elite soccer (Murr, Feichtinger, et al., 2018; Murr, Raabe, et al., 2018; Williams et al., 2020).

Therefore, the study of *Publication IV* includes unique aspects by analyzing the effect size of the connection of skills from both domains with success in youth and adult elite soccer players (cognition-success). Additionally, the majority of previous studies analyzed this connection in isolation by applying a monodisciplinary emphasis on physiological (e.g. speed and endurance) or physical (e.g. weight and height) factors in which the former is partially associated with success in soccer (Murr, Raabe, et al., 2018; Williams et al., 2020). Yet, success in complex high-performance environments like soccer relies on symbiotic and multidisciplinary factors as proposed by best practice recommendations which have been rarely used previously (Baker et al., 2020; Johnston et al., 2018; Rees et al., 2016; Till & Baker, 2020; Williams et al., 2020). Findings on the importance of executive functions for success in elite soccer are rare, especially across various developmental age phases since most of the studies used a monophasic analysis (Ivarsson et al., 2020; Johnston et al., 2018; Sakamoto et al., 2018; Vestberg et al., 2020; Vestberg et al., 2012; Vestberg et al., 2017; Williams et al., 2020). Furthermore, this high-performance-cognition research area is still in its beginning and also controversial (Beavan, Chin, et al., 2020; Beavan, Spielmann, et al., 2020) despite the promising findings of the cognition-success domain.

Another line of research related to high-performance suggests a connection of high injury-risks with lower cognitive and physical performance (Giesche et al., 2020a; Malone et al., 2019; Monfort et al., 2019; Swanik et al., 2007). Therefore, analyzing the contribution of both these aspects to injury incidence in elite soccer may yield valuable insights for the comprehension of injury mechanics in dynamic high-performance environments. Taken together, the gaps in current literature result in the research questions:

*IIIb:* To what extent are executive functions and physiological skills related to game time and injury absence?

*IIIc:* To what extent is age influencing these relationships?

#### *3.2.3.2 Answer to research question IIIb, IIIc and IIId*

My own research aims to fill some of the existing gaps in this cognition-success domain. My findings contribute to a better understanding of the relation of executive functions and physiological skills with game time and injury absence. *Publication IV* aims to analyze these objectives in youth and adult elite soccer players (i.e 12-34 years of age) concerning their multiphasic and multidisciplinary cognitive (objective and coach-rated) and physiological performance data in terms of their relation to success (cognition-success domain) by firstly investigating the connection to game time as a key performance indicator (Rumbold et al., 2020) and secondly, to injury incidences (i.e. contact and non-contact).

Executive functions and attention (multiple-object tracking) were examined due to their high relevance in elite soccer (Faubert, 2013; Huijgen et al., 2015; Romeas et al., 2016; Scharfen & Memmert, 2019; Verburgh et al., 2014; Vestberg et al., 2017). Further, physiological abilities concerning endurance performance (i.e. performance at the individual anaerobic threshold and YoYo intermittent recovery test) and physical performance (i.e. vertical jumps and sprint performance) were integrated as they represent relevant performance aspects (Abade et al., 2014; Bangsbo et al., 2008; Murr, Raabe, et al., 2018; Unnithan et al., 2012; Waldron & Murphy, 2013) and are typically analyzed in the domain of physiological talent prediction (Murr, Raabe, et al., 2018; Williams et al., 2020).

Taken together the investigation of *Publication IV* shows that a better performance in all executive functions (objective and coach-rated) except for inhibition is associated with the objective measure of successful performance in soccer within all included age groups to a lesser or greater degree. Cognitive flexibility and game intelligence are moderately to largely linked to game time, and working memory, the total cognition score and attention show small to moderate connections (see table 6). These results align with the small to moderately sized relation of executive functions and high-performance levels in *Publication I* and with research stating moderate effect sizes concerning the connection to assists and scored goals (Vestberg et al., 2020; Vestberg et al., 2012; Vestberg et al., 2017) along with approvals into a professional soccer academy only stating small effect sizes (Sakamoto et al., 2018).

These findings of previous studies are mostly based on the design fluency test measuring the higher-level executive functions problem-solving and planning (occasionally called metacognition or fluid intelligence, Diamond, 2013) consisting of working memory, cognitive flexibility, creativity and response inhibition (Sakamoto et al., 2018; Vestberg et al., 2017). Consequently, the diagnostics of executive functions in *Publication IV* differ as they measure isolated core executive functions in comparison to the unified measure of higher-level executive functions. It is argued that a similar executive decision-making chain like in actual soccer situations might be required for the design fluency test (Vestberg et al., 2017) with the particular functions of cognitive flexibility and working memory essentially driving this relationship with success as also indicated by the results of *Publication IV.* In comparison, the weakness of the design fluency test is the particular division which core executive function underlies a specific relationship. This is simultaneously the advantage of the segregated measures whereas the design fluency test may be more ecologically valid.

However, it is important that more data on the relation of executive functions and game time are collected because this parameter of success in *Publication IV* (i.e. game time) is probably even more valid as game time is regularly used since players of all positions can achieve it (Rumbold et al., 2020) in comparison to assists and goals representing a huge challenge for defending compared to striking positions.

Again, this connection of game time and executive functions is also represented in all teams groups since age did not meaningfully influence the relationship. Therefore, these results are complemented by the previous associations with game intelligence indicating an essential aspect of soccer expertise across all developmental stages from age 12 upwards. However, inhibition shows no correlation with game time in contrast to previous studies which presented small effect sizes (Verburgh et al., 2014; Verburgh et al., 2016). This difference could be based on the variations in previous investigations that i) analyzed differing age groups with 8-16 year-old players and ii) only used indirect measures of performance by distinguishing between elite and nonelite level of soccer players.

Concerning the physiological measures, age substantially influenced the association of the parameters sprint and repeated intense exercise ability with game time possibly based on the later maturation status of older compared to young players' physiological capacities leading to higher endurance performance and faster sprint times. The partial correlation analysis removed this age influence and revealed the moderately sized relationships of sprint time (5- and 30-meters) and the repeated intense exercise ability with game time, confirming moderate effects regarding their association with success (measured by the entry into a subsequent performance phase of a youth elite academy) in a prior review (Murr, Raabe, et al., 2018) and the association of running performance with goal scoring in soccer (Klemp et al., 2021). These relationships appear intuitive because they represent key performance indicators in soccer (Oone et al., 2012; Reilly et al., 2000), but it needs to be considered that the repeated intense exercise ability test of *Publication IV* and the endurance tests of the review differ slightly. In contrast to moderate effect sizes of previous review findings (Murr, Raabe, et al., 2018) no other physiological measure was meaningfully linked to game time.

In summary, the present results indicate that executive functions (without inhibition) besides physiological skills of sprint and repeated intense exercise ability are meaningfully linked to elite soccer player’s game time. Hereby, one needs to consider that the cognitive parameters are based on larger sample sizes compared to the physiological measures of repeated intense exercise ability, squat jump and performance-IAT. Moreover, the present results also partially answer the question whether domain-generic executive functions are linked to success in elite soccer (Beavan et al., 2020).

The secondary aim of *Publication IV* was to investigate to what extent the multidisciplinary performance parameters are linked to injury incidence (research question IIIc). In terms of contact injuries, no meaningful association was present except for the small to moderate, negative one with the 30-meter sprint time. Age had a large influence on this association, again possibly based on the earlier maturation status accompanied by the slower sprint times of younger- (i.e. U13-U15) in comparison to older players. The absence of any injury incidence in this age groups biased the first bivariate correlation analysis before age was controlled for. This opposes the fourth hypothesis of *Publication IV* as it indicates a higher injury incidence in players with better sprint times which is contradictory to prior findings of better sprint performance resulting in a reduced injury risk in adult elite soccer players (Malone et al., 2018). However, it is unknown if the association of the previous study (Malone et al., 2018) is present in every injury type (e.g. contact vs noncontact) as faster players may be challenged in a greater number of duels leading to more contacts which would result in a heightened risk of injury. Since 92% of the contact injuries belong to the lower extremities (see Appendix), it indicates that faster players’ higher speed intensifies those duel-contacts with other players leading to an increased risk of injury. The heightened mechanical load in faster players may be another aspect resulting in this increased risk (Beato & Drust, 2020) although one needs to consider the complete absence of injuries in the teams U13-15. The present study is the first one showing this relationship.

Furthermore, no association of executive functions and contact- or noncontact injuries was found in *Publication IV* which contradicts the second hypothesis and previous results stating moderate to large effect sizes for this relation (Giesche et al., 2020b; Monfort et al., 2019; Swanik et al., 2007). This discrepancy could be due to the differing study settings since the previous investigations predominantly examined amateur athletes from several sports in mainly controlled test conditions.

The second injury category “noncontact” showed a moderate to large association with sprint (30-meters) suggesting a decreased noncontact injury incidence in players with higher speed which is in agreement with our hypothesis and previous investigations indicating the same relation (Malone et al., 2018, 2019). The distribution of 50% of the noncontact injuries to the musculature is in agreement with the previously indicated injury-risk reduction by well-developed muscles contributing to sprinting (Malone et al., 2018, 2019). The current results revealing the influence of the player’s age on this association represent an important expansion.

Finally, the results indicate that a decreased probability of noncontact injuries may be accompanied by sophisticated anaerobic endurance performance since performance-IAT and noncontact injuries show a negative and small to moderate correlation (see table 7). Since fatigue leads to a heightened risk of injuries based on poorer coordination besides other aspects grounded in decreased neuromuscular control (Huygaerts et al., 2020), players with better IAT performance become fatigued later and probably have a reduced risk of injury. The protective mechanism of well-trained cardiovascular and musculoskeletal structures (Gabbett, 2016) is also in agreement with this relationship. The moderator variable of age again moderately influenced both linkages alike the contact injuries. However, the absence of the performance-IAT parameter in the teams U13-U15, U23 and first team needs to be taken into consideration.

Concerning a performance needs-analysis these findings represent valuable insights into the actual high-performance demands in multivarious team sports like soccer (Baker et al., 2020) along with an expansion of current knowledge of cognitive and physiological connections with skill level and talent in several age groups (Baker et al., 2019, 2020; Johnston et al., 2018; Till & Baker, 2020).

Table 6. *Partial correlations between executive functions, physiological abilities and game time whilst controlling for age group (from Publication IV)*

| | Game Intelligence | Selective Attention | Working Memory | Cognitive Flexibility | Inhibition | Cognition Score |
|---|---|---|---|---|---|---|
| Game time | | | | | | |
| Spearmans’s *r* | **0.42** | **0.22** | **0.29** | **0.34** | -0.17 | **0.29** |
| CI | **0.25, 0.56** | **0.02, 0.40** | **0.12, 0.44** | **0.18, 0.48** | -0.33, 0.01 | **0.10, 0.46** |
| *n* | **109** | **97** | **128** | **128** | 131 | **100** |

| | | | | | | |
|---|---|---|---|---|---|---|
| Included teams | U13-first team | U15-first team | U13-first team | U13-first team | U13-first team | U15-first team |

| | RIEA | Sprint (5M) | Sprint (30m) | Squat Jump | Counter Movement Jump | Drop Jump | Performance-IAT |
|---|---|---|---|---|---|---|---|
| Game time | | | | | | | |
| Spearmans's *r* | **0.32** | **-0.34** | **-0.37** | -0.01 | 0.04 | 0.14 | 0.16 |
| CI | **0.10, 0.54** | **-0.50, -0.16** | **-0.53, -0.19** | -0.27, 0.25 | -0.14, 0.22 | -0.04, 0.31 | -0.15, 0.44 |
| *n* | **56** | **103** | **103** | 56 | 122 | 122 | 42 |
| Included teams | U14-U19 | U13-U23 | U13-U23 | U15-U19 | U13-first team | U13-first team | U16-U19 |

*Note.* RIEA: repeatedly intense exercise ability; IAT: individual anaerobic threshold; boldface numbers highlighting CIs not including zero

Table 7. *Partial correlations between executive functions, physiological abilities and injuries whilst controlling for age group (from Publication IV)*

| | Game Intelligence | Selective Attention | Working Memory | Cognitive Flexibility | Inhibition | Cognition Score |
|---|---|---|---|---|---|---|
| Contact Injury | | | | | | |
| Spearmans's *r* | -0.14 | 0.04 | -0.02 | 0.12 | -0.08 | -0.04 |
| CI | -0.31, 0.04 | -0.15, 0.23 | -0.18, 0.15 | -0.05, 0.30 | -0.24, 0.09 | -0.23, 0.15 |
| *n* | 122 | 108 | 141 | 141 | 141 | 108 |
| Noncontact Injury | | | | | | |
| Spearmans's *r* | 0.08 | -0.14 | 0.11 | 0.05 | 0.16 | 0.14 |
| CI | -0.10, 0.25 | -0.32, 0.10 | -0.10, 0.27 | -0.12, 0.21 | -0.01, 0.32 | -0.05, 0.32 |
| *n* | 122 | 108 | 141 | 141 | 141 | 108 |
| Included teams | U13-first team | U15-first team | U13-first team | U13-first team | U13-first team | U15-first team |

| | RIEA | Sprint (5M) | Sprint (30m) | Squat Jump | Counter Movement Jump | Drop Jump | Performance -IAT |
|---|---|---|---|---|---|---|---|
| Contact Injury | | | | | | | |
| Spearmans's *r* | 0.08 | -0.08 | **-0.24** | 0.09 | 0.12 | 0.04 | -0.04 |
| CI | -0.18, 0.33 | -0.26, 0.10 | **-0.41, -0.06** | -0.16, 0.33 | -0.05, 0.28 | -0.13, 0.21 | -0.32, 0.25 |
| *n* | 61 | 115 | **115** | 66 | 134 | 134 | 48 |
| Noncontact Injury | | | | | | | |
| Spearmans's *r* | -0.20 | 0.11 | **0.35** | -0.12 | -0.19 | 0.16 | **-0.29** |
| CI | -0.43, 0.05 | -0.07, 0.30 | **0.18, 0.50** | -0.35, 0.13 | -0.35, 0.02 | -0.01, 0.32 | **-0.53, -0.01** |
| *n* | 61 | 115 | **115** | 66 | 134 | 134 | **48** |
| Included teams | U14-U19 | U13-U23 | U13-U23 | U15-U19 | U13-first team | U13-first team | U16-U19 |

*Note.* RIEA: repeated intense exercise ability; IAT: individual anaerobic threshold; included teams: describes which teams contribute to the sample of each; boldface numbers highlighting CIs not including zero

Taken together, research questions IIIb and IIIc can be answered as follows based on the results of *Publication IV:*

*IIIb:* For all executive functions and the combined cognition value except for inhibition there are small to large correlations with game time. Further, sprint time and repeated intense exercise ability are small to moderately correlated with game time.

*IIIc:* None of the executive functions show meaningful associations with contact or noncontact injury incidence. 30-meter sprint time is associated to a various degree with contact- (i.e. negative linkage) and noncontact injury incidence (i.e. positive linkage). Lastly, performance-IAT is small to moderately, negatively related to noncontact injury incidence.

*IIId:* The moderator variable age does not influence the association of executive functions with game time. Contrary, age influenced the relation of executive functions with noncontact injury incidence small to moderately (i.e. with working memory and inhibition). The correlation of the physiological parameters sprint and repeated intense exercise ability with game time is small to moderate in effect by age as well as the association of sprint (i.e. 30-meter time), squat- and countermovement jump and performance-IAT with noncontact injuries.

## 3.3 Training of cognitive functions in elite soccer players

The previous Chapters 3.2.1, 3.2.2, 3.2.3 along with the *Publications II, III* and *IV* suggest a widespread connection of executive functions with essential aspects of elite soccer across the domains of cognition-motor, cognition-cognition and cognition-success. Thus, executive functions seem to be of high relevance in elite soccer players' performance. Consequently, researchers and practitioners alike are very interested in the enhancement of these executive functions which is the main focus of the present section.

### 3.3.1 Previous research

Another line of research concerning executive functions in high-performance sports besides the expansion of knowledge on the particular associations with aspects like success, injuries and motor performance is the improvement of these executive functions. The superiority of athletes concerning their visual and executive functions has attracted increasing interest throughout several research areas like sport science, cognitive neuroscience and sport psychology (Callan & Naito, 2014; Huang et al., 2017; Yarrow et al., 2009a). This is also based on aspects like the higher success rate of elite soccer players with better domain-general visual abilities like depth perception and visual clarity (Burris et al., 2019; Roberts et al., 2017). These domain-general visual as well as executive functions are closely related to each other, however they need to be distinguished clearly so that one may further operationalize them. The visual system yields sensory information from the surroundings and is mostly based on afferences (i.e. input streams to the brain) and its basic processing compared to the task of the executive functions to also conduct more sophisticated processing and put this sensory information into context to make decisions (Gilbert & Burgess, 2008).

Another track of research shows positive effects of physical activities on cognitive skills by stimulating neurotropic chemicals like BDNF (i.e. brain-derived neurotrophic factor) or initiating increased cerebral oxygen supply (Cox et al., 2016; Prakash et al., 2015). This physical uplifting along with elite soccer players' cognitive advantages may suggest that these skills are implicitly practiced during continuous soccer training; but this notion is not conclusive as it is mainly based on cross-sectional findings.

Moreover, the superiority of elite athletes concerning their visual and executive functions as also shown in *Publication I* and in previous research leads to a very high interest to examine approaches and tools to improve these skills. One of these approaches is the component skills approach focusing on the training of essential subprocesses (Appelbaum & Erickson, 2018; Hadlow et al., 2018). One often used training tool belonging to this methodology is the NeuroTracker$^{TM}$ (NT) 3 dimensional (3D) multiple-object tracking (MOT) (Faubert, 2013; CogniSens Athletics Inc., Université de Montréal).

Longitudinal training studies applying this tool with adolescent athletes provide mixed evidence. For example, Parsons et al. (2016) investigated the effect of five weeks of training on students by means of an electroencephalogram and neuropsychological diagnostics. They stated improvements in working memory, attention, visual information processing and more utilizable neural resources whereas the used working memory test mainly examined short-term memory functions and needs to be considered with caution. Another investigation by Fleddermann et al. (2019) examined working speed, memory span, processing speed, sustained attention, and a volleyball-specific motor test in elite volleyball athletes and an active control group after eight training weeks. They found meaningful enhancements in sustained attention and processing speed, but one needs to consider the inclusion of volleyball-specific motor activities in the training intervention. Romeas et al. (2016) examined small-sided soccer matches before and after a five-week long training period in an active and passive control group with amateur soccer players and stated enhanced passing decision-making precision. In contrast to the improvements in these studies, no significant enhancements in executive functions were achieved in athletes from several dynamic sports after a five-week training program (Moen et al., 2018); in these cases the large variation in conducted trainings among the athletes biases these findings.

A main feature of the NT 3D-MOT is that the task difficulty adapts based on the previous performance. Two contrary theories regarding this adaptability exist which aim to describe the variations in performance improvements after training. Firstly, the magnification theory postulates that the largest performance increase after cognitive training occurs in individuals already scoring high in cognitive performance as they may have a greater amount of cognitive resources for the acquisition of new skills. Secondly, the compensation theory proposes a greater performance increase in individuals with low cognitive performance since they may have a larger space for improvement (Karbach & Unger, 2014).

The present overview of present findings on NT 3D-MOT training in adolescent athletes only shows improvements in simple cognitive functions like processing speed whereas no enhancements of higher-level cognitive mechanisms like executive function are present with the exception of attention. Additionally, although physical activity is an important influence on cognitive skills (Cox et al., 2016; Prakash et al., 2015), this moderator variable has not been analyzed in the previous studies which may have biased the stated enhancements after NT 3D-MOT training. It is also unknown if the small improvements in basic cognitive skills are grounded in this particular domain or whether these are due to improved visual functions. This vagueness relates to the phenomenon of transfer including the divergent narrow and broad transfer theories (Furley & Memmert, 2011). This transfer phenomenon has been specified into the classifications of task-specific (i.e. enhancements in the trained task), near (i.e. improvements in a similar cognitive task), further (i.e. improvements in other unrelated cognitive tasks) and far transfer (i.e. improvements in transfer to competition) (Zentgraf et al., 2017).

Concerning these transfer classifications, the investigation showing the largest further-transfer effects examined university students (Parsons et al., 2016). Therefore, one needs to

be careful when generalizing these findings with regard to an elite athlete population as learning curves of students and elite athletes vary considerably (Faubert, 2013). Thus, it is unknown if the training gains are simply based on the benefits of the physical exercises and three of four investigations applied a comparably short training duration of five weeks possibly leading to a reduced representation of training gains. This considerable heterogeneity in the findings and methods of current studies lead to a general examination of the inclusion of visual and executive functions in the NT 3D-MOT. The task demands are highly specific without the involvement of other cognitive or visual elements apart from the MOT skill which shows that the representation of these aspects is comparably low (see Appendix). However, various counter arguments claimed near and further transfer effects of NT 3D-MOT training to visual abilities like depth perception, visual field and attention (Faubert & Sidebottom, 2012; Parsons et al., 2016). The scarce data underpinning these arguments are complemented by the low theoretical likelihood to achieve the claimed transfer effects. By also considering the heterogenous findings on the transfer effects of NT 3D-MOT it seems crucial to rigorously analyze this tool regarding its practical relevance (C. Walton et al., 2018). This results in the specific research question IV: “To what extent does a multiple-object tracking training tool enhance the cognitive performance of elite soccer players?” The sub-questions are:
*IVa:* To what extent does near or far transfer to visual or executive functions occur?
*IVb:* To what extent does baseline performance relate to training gains?

### 3.3.2 Answer to research question IVa and IVb

My own research aims to examine some of the heterogeneities regarding the transfer effects of NT 3D-MOT by adhering to recent suggestions (Harris et al., 2018; Walton et al., 2018). *Publication V* investigates the extent of potential transfer effects of the NT 3D-MOT single task to visual and executive functions by studying 29 elite soccer players of 17-21 years of age in a 10-week training intervention. Another aim is the analysis of the association of baseline performance with subsequent training gains.

These transfer effects were analyzed concerning the visual functions based on their essential relevance in the perception-process (Burris et al., 2019; Hüttermann et al., 2014) and the executive functions due to their present importance in elite soccer (Huijgen et al., 2015; Verburgh et al., 2014; Verburgh et al., 2016; Vestberg et al., 2012; Vestberg et al., 2017). The moderator variable of physical activity was integrated to control for potential effects on the results.

The analysis of the study in *Publication V* suggests that the NT 3D-MOT evokes large task-specific and near-transfer effects to the NT 3D-MOT and MOT skills. However, it does not lead to further-transfers to visual and executive functions that are not explicitly trained since no meaningful adaptations occurred (see table 8). This lack of further-transfer may be explained by the missing demands of the NT 3D-MOT concerning the visual and executive functions as shown by the initial evaluation (see Appendix). The specificity of the task contains several elements of dynamic game situations whereas the combination of perception and action of these situations is not represented (Romeas et al., 2019). This may contribute to the lack of further transfer as well, which is also in line with present reviews (Diamond & Ling, 2016; Hadlow et al., 2018) and previous null-findings (Fleddermann et al., 2019; Moen et al., 2018). Therefore, the description of NT 3D-MOT as being a “Gold Standard Cognitive Enhancer” (Parsons et al., 2016, p. 3) which improves executive functions and several visual skills, like depth perception and the visual field (Faubert & Sidebottom, 2012; Parsons et al., 2016), is challenged significantly by the present absence of further effects. This absence vice versa supports the statement that a very specific targeting of particular executive functions needs to be present to enable training effects (Diamond & Ling, 2016).

However, contrary to the absence of transfer in the present study, processing speed, sustained attention (Fleddermann et al., 2019) and working memory function (Parsons et al., 2016) have been improved in previous investigations. And yet the task-specific and near-transfer effects to NT 3D-MOT and MOT (see Figure 3 and 4) align with the previous findings of the athletes’ remarkable competence to adapt to a dynamic und unpredictable tracking task (Faubert, 2013; Fleddermann et al., 2019).

*Table 8. Mean results of all tests (pre- and posttests) for both groups (from Publication V)*

*Note:* [a] = lower score indicating better performance; ES = effect size (*d*); the group's performance level in the pretest did not differ substantially except for visual clarity. All scores are further described in the method section.

| | Intervention Group | | | | | |
|---|---|---|---|---|---|---|
| | Pretest | | Posttest | | Change (CI 95%) | ES |
| | *M* | SD | *M* | SD | | |
| NeuroTracker speed threshold | 1.45 | 0.57 | 2.53 | 0.41 | 1.08 (0.81 to 1.38) | 2.2 (1.3, 3) |
| Attention Window in degree | 11.38 | 6.24 | 19.22 | 6.57 | 7.79 (3.87 to 11.70) | 1.22 (0.5, 2) |
| Working Memory score in % | 71.06 | 10.34 | 79.6 | 8.42 | 8.52 (5.85 to 11.21) | 0.91 (0.2, 1.5) |
| Metacognition score | 12.9 | 1.66 | 15 | 1.88 | 2.10 (0.87 to 3.32) | 1.17 (0.3, 1.8) |
| Cognitive Flexibility in s[a] | 28.56 | 8.59 | 21.00 | 8.40 | -8.57 (-12.04 to -5.07) | 0.89 (0.2, 1.5) |
| Visual Clarity score | 12.37 | 96.63 | 38.07 | 137.41 | 25.63 (-26.67 to 77.87) | 0.22 (-0.5, 0.8) |
| Contrast Sensitivity score | 1.90 | 0.18 | 1.90 | 0.17 | 0 (-1.0 to 1.0) | 0 (-0.7, 0.7) |
| Depth Perception score | 189.81 | 79.97 | 193.43 | 73.00 | 4.31 (-28.84 to 37.47) | 0.05 (-0.5, 0.6) |
| Near-Far Quickness score | 28.20 | 7.13 | 31.27 | 7.43 | 3.07 (-0.27 to 6.42) | 0.41 (-0.3, 1) |
| Target Capture score[a] | 176.67 | 46.74 | 190.00 | 58.09 | 18.75 (-51.91 to 14.41) | 0.24 (-1, 0.3) |
| Perception Span score | 48.38 | 9.41 | 49.63 | 9.22 | 0.92 (-1.86 to 3.74) | 0.12 (-0.6, 0.7) |
| Multiple Object Tracking score | 2107.69 | 862.48 | 2570.36 | 559.64 | 462.68 (148.53 to 776.81) | 0.64 (-0.1, 1.2) |
| Inhibition score | 9.87 | 5.54 | 14.00 | 4.74 | 4.12 (1.95 to 6.32) | 0.8 (0.1, 1.4) |
| Reaction time in ms[a] | 300.60 | 27.59 | 284.20 | 20.33 | -16.4 (-26.36 to -6.44) | 0.6 (0.1, 1.4) |

| | Control Group | | | | | |
|---|---|---|---|---|---|---|
| | Pretest | | Posttest | | Change (CI 95%) | ES |
| | *M* | SD | *M* | SD | | |
| NeuroTracker speed threshold | 1.18 | 0.37 | 1.61 | 0.49 | 0.43 (0.19 to 0.65) | 0.99 (0.2, 1.7) |
| Attention Window in degree | 12.36 | 6.22 | 18.7 | 6.82 | 6.33 (3.76 to 8.91) | 0.96 (0.2, 1.8) |
| Working Memory score in % | 65.38 | 10.32 | 73.69 | 10.33 | 8.31 (2.99 to 13.63) | 0.81 (0.1, 1.5) |
| Metacognition score | 13.19 | 1.62 | 14.57 | 1.66 | 1.37 (0.26 to 2.51) | 0.83 (0, 1.5) |
| Cognitive Flexibility in s[a] | 29.97 | 10.31 | 19.60 | 9.07 | -9.11 (-13.40 to -4.73) | 1.07 (0.2, 1.9) |
| Visual Clarity score | 86.62 | 65.86 | 74.78 | 61.91 | -11.82 (-55.67 to 32) | -0.19 (-1, 0.6) |
| Contrast Sensitivity score | 1.92 | 0.13 | 1.74 | 0.46 | -0.17 (-0.43 to 0.07) | -0.52 (-1.3, 0.3) |
| Depth Perception score | 170.31 | 89.19 | 159.13 | 83.25 | -11.18 (-52.44 to 30.08) | -0.13 (-0.9, 0.5) |
| Near-Far Quickness score | 24.15 | 6.87 | 31.38 | 4.68 | 7.22 (3.17 to 11.28) | 1.23 (0.4, 2.1) |
| Target Capture score[a] | 203.85 | 70.60 | 223.08 | 89.83 | 19.22 (-46.92 to 8.46) | 0.24 (-1, 0.4) |
| Perception Span score | 41.31 | 9.91 | 46.23 | 12.34 | 4.91 (-0.31 to 10.16) | 0.44 (-0.3, 1.2) |
| Multiple Object Tracking score | 1853.41 | 691.27 | 1791.39 | 491.49 | -62.01(-295.70 to 171.68) | -0.13 (-0.9, 0.7) |
| Inhibition score | 12.00 | 5.28 | 12.92 | 4.65 | 0.91 (-1.74 to 3.60) | 0.19 (-0.6, 1) |
| Reaction time in ms[a] | 301.62 | 22.05 | 286.31 | 14.65 | -15.31 (-23.22 to -7.40) | 0.82 (0, 1.5) |

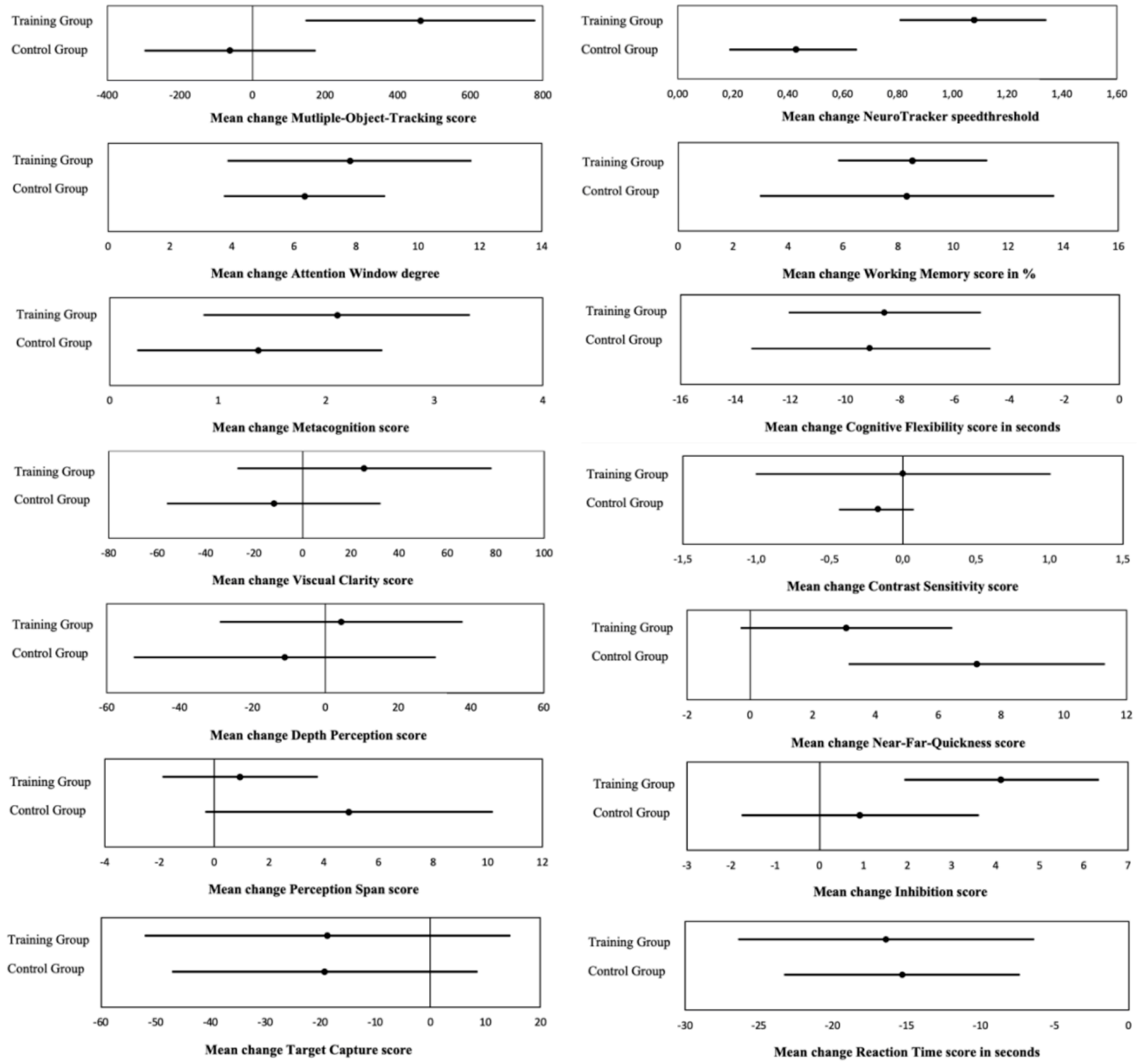

*Figure 3.* Mean performance changes with 95% CI of all tests for both groups (from *Publication V*).

This may also affirm the proof of concept concerning the general trainability of cognitive skills from a fundamental perspective (Bryck & Fisher, 2012; Fields, 2015), although this seems only feasible with near-transfer effects, at least in the NT 3D-MOT. Moreover, the present findings in *Publication V* may refine the previous results showing increases in NT 3D-MOT performance and a transfer effect to decision-making in soccer (Romeas et al., 2016). Specifically, these transfer effects may probably be based on the task-specific MOT improvements rather than on enhancements of visual or executive functions. Nevertheless, the MOT skill in isolation still appears to have a high relevance for dynamic sports as also shown in *Publication I* and other studies (Mangine et al., 2014; Scharfen & Memmert, 2019). This results in a large interest to train it as it is suggested to enhance decision-making skills at least for amateur athletes (Romeas et al., 2016). As elite athletes are already on a cognitive high-performance level even slight enhancements as seen in the present study (see table 8) might represent an important adaptation for game performance. Additionally, the single-task NT 3D-MOT training applied in the present publication only represents the initial phase of challenge in the general progression of the training. Thus, no inferences can be made concerning dual-task NT 3D-MOT training paradigms.

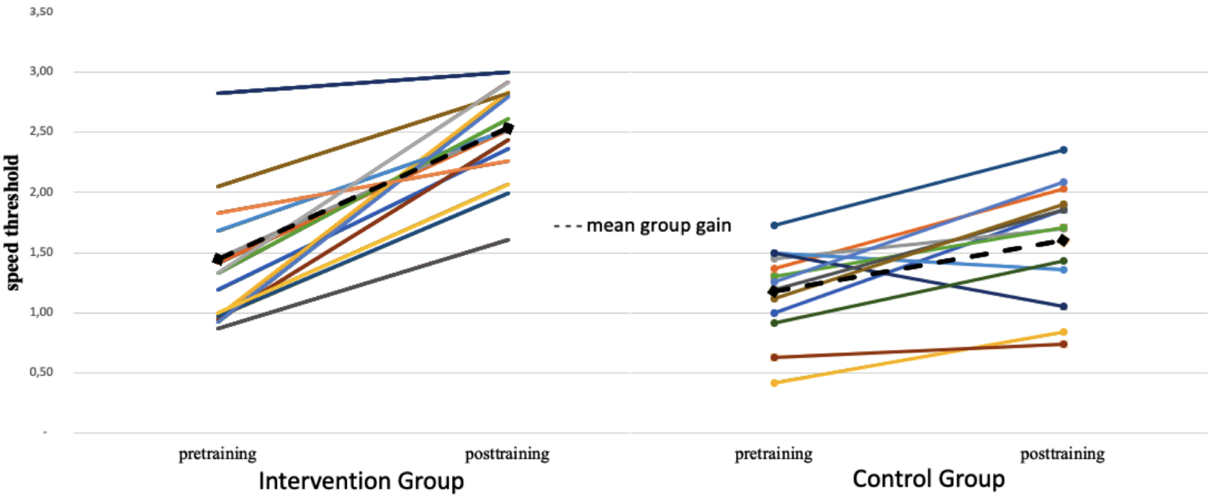

*Figure 4.* Mean speed thresholds of the NT 3D-MOT of all athletes are represented in continuous lines whereas dashed lines represent mean speed threshold gains (from *Publication V)*.

Since the moderator variable of physical activity shows only small to moderate differences the adaptations seem to be mostly grounded in the cognitive training. Furthermore, the study also aimed to investigate the magnification versus compensation theory. The large negative correlation between the baseline performance in the NT 3D-MOT, perception span, target capture and the NT 3D-MOT training gains seems to favor the compensation theory. The theory postulates large improvement potentials when individuals with poorer cognitive performance train cognitively since their improvement scope seems to be comparably large.

Summed up, research questions IVa and IVb can be answered as follows based on the findings of *Publication V:*

*IVa:* The NT 3D-MOT training appears to evoke large task-specific and near transfer effects to the MOT skills but no further transfer to any other visual or executive function.

*IVb:* The NT 3D-MOT baseline performance relates largely to the NT 3D-MOT training gains favoring the compensation theory.

# 4 Conclusion and prospect

This chapter elaborates on the synopsis of the presented work of the thesis and summarizes its indications for theory and practice. Moreover, limitations of the presented studies and possible paths for future research in the field of cognitive performance in elite athletes will be discussed.

## 4.1 Aim of the thesis and summary of key results

The overall aim of this thesis was to resolve the underlying mechanisms of cognitive functions in high-performance team sports with a special focus on executive functions and elite soccer. The role of cognitive functions in elite soccer was operationalized by classifying them into five different areas to create a holistic and comprehensive framework of the underlying mechanisms: I examined the association of cognition with i) skill levels (*cognition-expertise domain)*, ii) motor and physiological performance *(cognition-motor domain)*, iii) coach-rated game intelligence *(cognition-cognition domain)*, iv) game time and injury absence *(cognition-success domain)* and lastly v) the training of certain cognitive functions *(cognition-training domain)*. Table 9 reviews the empirical answers gathered from my own research to the research questions stated at the beginning of this thesis.

Table 9. *Answer to Research Questions addressed in the Thesis*

| | |
|---|---|
| *I. How do cognitive functions relate to expertise and skill level in high-performance athletes? (cognition-expertise domain)* | |
| Ia. To what extent do domain-general cognitive functions differ among elite athletes/ experts and amateurs? | The meta-analytic review demonstrated that the extent to which elite/ expert athletes and non-elite/ non-expert athletes differ in their domain-general cognitive performance is small to medium sized favoring a superiority of elite/ expert athletes. |
| IIa. To what extent are skill definition, age and examined cognitive areas influencing this difference? | The influence of skill definition on the difference in cognitive functions is small to medium sized as the “elite” definition yields a greater effect size compared to the “expert” definition. The effect of age on the difference in cognitive functions is almost not existent similar to the influence of different cognitive areas. |
| *II. How do cognitive functions relate to motor and physical skills in elite soccer players? (cognition-motor domain)* | |
| IIa. How large is the effect size of the relationship between cognitive functions and motor as well as physical skills in elite soccer players? | In two studies we found meaningful but specific relationships of certain cognitive functions and motor skills. Specifically, working memory shows the most consistent connection to the maximal anaerobic parameter sprint and soccer-specific activities with ball (e.g. dribbling) with small to large effect sizes. Similarly, cognitive flexibility is small to moderately linked to the maximal |

| | |
|---|---|
| | anaerobic parameters sprint and drop jump performance. |
| IIb. To what extent is age influencing this relationship? | No generalizing answer can be given as age does not commonly influence all but only specific cognition-motor relationships with small to large effect sizes. Some other associations – especially concerning working memory and cognitive flexibility linkages – are not substantially influenced by age indicating a fundamental relationship across several developmental phases. |
| *III. How do executive functions contribute to success in elite soccer players? (cognition-cognition and cognition-success domain)* | |
| IIIa. How large are the effect sizes of the relationships between executive functions and game intelligence and the influence of age on them? | In one study we demonstrated that the meaningful connection between the executive functions of working memory and cognitive flexibility and coach-rated game intelligence is small to moderately sized across all tested age groups (12-34 years of age). |
| IIIb. To what extent are executive functions (i.e. objective and coach-rated) and physiological skills related to game time and injury absence? | All executive functions and the combined cognition value except for inhibition are small to largely correlated with game time along with small to large correlations of sprint time and repeated intense exercise ability with game time. |
| IIIc. To what extent are executive functions (i.e. objective and coach-rated) | |

| | |
|---|---|
| and physiological skills related to injury absence? | None of the executive functions show meaningful associations with contact or noncontact injury incidence whereas 30-meter sprint time is small to largely associated with contact- (i.e. negative linkage) and noncontact injury incidence (i.e. positive linkage). There is also a negative small to moderate relation of performance-IAT and noncontact injury incidence. |
| IIId. To what extent is age influencing relationships of b) and c)? | The moderator variable age did not influence the association of executive functions with game time whereas its relation to noncontact injury incidence was small to moderate influenced (i.e. in connection with working memory and inhibition). The correlation of the physiological parameters sprint and repeated intense exercise ability with game time were small to moderately affected by age as well as the association of sprint, squat- and countermovement jump and performance-IAT with noncontact injuries. |
| *IV. To what extent does a multiple-object tracking training tool enhance the cognitive performance of elite soccer players?* | |
| IVa. To what extent does near or far transfer to visual or executive functions occur? | We demonstrated in one experiment that the NT 3D-MOT training appears to evoke large task-specific and near transfer-effects to the MOT skills but no further-transfer to any other visual or executive function. |
| IVb. To what extent does baseline performance relate to training gains? | |

|  |  |
|---|---|
|  | The NT 3D-MOT baseline performance relates largely to the NT 3D-MOT training gains favoring the compensation theory. |

The different domains which were examined are depicted in Figure 5 to visualize the synopsis of this thesis. Like the basic figure with all arrows pointing to the cognitive functions and high-performance in elite soccer depicts, all five investigated cognition domains contribute to high-performance in soccer in distinct ways. Taken together, cognitive functions discriminate elite and non-elite athletes in the first place as evident in the cognition-expertise domain (*Publication I)*. Elite soccer, as being one of the team sports in which this discrimination has recently been researched shows that certain but not all cognitive functions relate to the motor (*Publication II & III)*, the cognition and the success domain (*Publication IV)* with working memory and cognitive flexibility showing the most consistent relations across domains and multiple-object tracking representing noticeable but less consistent relations confirming previous proposals of their importance (Faubert & Sidebottom, 2012; Furley & Memmert, 2010; Mangine et al., 2014; Vestberg et al., 2020). The cognition-motor connections in particular suggest that cognitive functions are not only an end in themselves but are also crucial for those other domains. This can be connected to statements that cognitive functions have primarily evolved to serve and enable the execution of motor functions have increased in complexity during the human evolution (Leisman et al., 2016). However, the demands of our environments on cognitive functions are not only the facilitation of optimal motor functioning but also the perception and processing of large information streams appearing in those environments. The combination of these information processing demands with the proposed serving of complex motor functions may overload even the most sophisticated cognitive system (Marois & Ivanoff, 2005; Cohen et al., 2015) - or phrased differentially as cited in the beginning of this thesis: “We are ancient brains in a high-tech world” (Gazzaley & Rosen, 2016, p. xv, prologue).

This cognitive overload may be especially present in elite sports like soccer, as it represents one of the biggest challenges for the brain (Walsh, 2014). Thus, taken together the combination of cognitive involvements in the ceaseless planning and execution of success-related motor tasks (e.g. Klemp et al., 2021) besides the always present information processing demands in highly complex and dynamic elite soccer situations may account for the small to moderate relation of three of four tested cognitive functions with game time. These small to moderate effect sizes may even be interpreted with a higher value when considering that it is unlikely that the players with the best game intelligence and cognitive performance played every possible minute like they normally would when the only argument for getting game time would be the player's performance (i.e. in the study context of *Publication IV)*. This unlikeliness is based on the youth academy's philosophy to give every player sufficient game time regardless of their current performance level especially in the younger teams. Of course, better players still play more often than players with poorer performance, but this is not absolutely and solely based on their current performance levels.

Further, the small to moderate relation with game intelligence in the cognition-cognition domain further underlines the relevance of cognitive functions for high-performance in soccer but also indicates that game intelligence not only consists of cognitive functions. Other aspects like visual functions to perceive situations properly, soccer-specific tactical knowledge to act optimally in these situations and experience in high-performance divisions probably also contribute to it.

Lastly, the multiple-object tracking skill has been shown to evoke task-specific and near-transfer effects to this specific skill in the training domain while providing results indicating the compensatory effects regarding training gains (*Publication V)*.

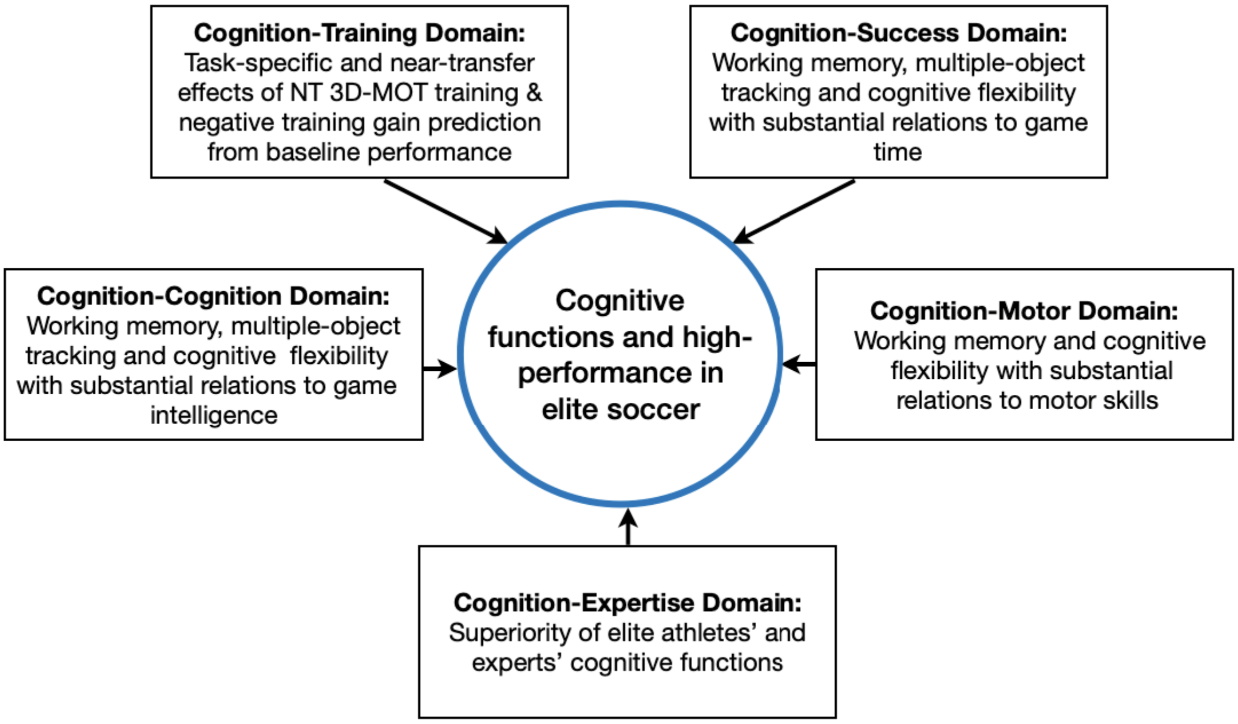

*Figure 5.* Simplified graphic of the empirical key findings in this thesis.

This synopsis also aims to foster basic knowledge of cognitive functions in sports. As stated in the beginning of this thesis, studies belonging to the expert-performance approach claim the elite athletes’ superiority in domain-specific cognitive functions (Mann et al., 2007). In a complementary manner, the findings of this thesis also show the superiority of elite athletes’ domain-general cognitive functions (*Publication I)*. When combining both approaches a unifying framework appears indicating an overall cognitive superiority of elite athletes’ cognitive functions, which may be based on their sophisticated cognitive skills, which also spreads out into the specifics of their particular type of sport like the specific visual scanning activity and decision-making (Aksum et al., 2021; Roca et al., 2021). Further, it also appears that this cognitive superiority does not exist in isolation but is rather intertwined with other performances of the brain (e.g. game intelligence) and the body (e.g. motor and physiological performance). This interconnectedness is not only present on an indirect level by relating to other performance domains that are associated with success (e.g. Klemp et al., 2021), but also on a direct level by showing meaningful relations to game time. When summarizing these findings, again from the perspective of the first principle thinking method, the paramount importance of the underlying central nervous system functioning like a central governor for all performance domains may be stressed. Previous research already stated that the central nervous system directly governs cognitive performance (Bagarinao et al., 2019), motor performance (Taubert et al., 2011) and skill acquisition/expertise (Chang, 2014) with distinct processes like neurochemical activity driving prolonged effort (Walton & Bouret, 2019) like in endurance performance both in cognitive (Kunrath et al., 2020; Smith et al., 2016) and physiological activities (Brown et al., 2019; Pageaux et al., 2014; Pageaux & Lepers, 2018; Smith et al., 2018; Staiano et al., 2018). However, large-scale multidisciplinary and multiphasic performance data on some of these relations are present in this thesis for the first time. Therefore, it is even more surprising that, despite the governing function of the underlying central nervous system and previous literature on injury risks and cognition, no meaningful associations of cognitive skills with injury incidences are present. However, this could also stem from the cognitive measures which do not represent the whole range of processes of the central nervous system like for example brain network connectivity (Diekfuss et al., 2018). Further, a unique feature of the central nervous system, here partially represented by the cognitive functions, is its functional adaptability called neuroplasticity (Grooms et al., 2015) which is indicated by the demonstrated trainability of very specific but not general cognitive skills (*Publication V)*.

In short, the findings of this thesis demonstrate how the brain is able to achieve extraordinary accomplishments like performing in elite sport situations to partially answer the initially posted question "what makes the best the best?" (Walsh, 2014, p.2). The findings of this thesis show that certain cognitive functions are highly relevant for making the best the best in a globally widespread team sport like soccer with over 265 million players worldwide (FIFA, 2013). Considering these findings concerning the upper limits and possible achievements of human performance from a more general perspective, they could also shed light on how cognitive functions in multidisciplinary and multiphasic contexts may relate to performance in other domains of human high-performance like musical expertise or medical endeavors like emergency surgery. Similar to the classification of training related transfer effects in *Publication V* such possible handovers to other high-performance domains may represent a near-transfer.

Further, these results from population outliers (i.e. elite athletes) may also be informative for the normal population representing further-transfer effects. For example, they may hint at the model of embodied cognition proposing that states of the brain influence states of the body and vice versa (Wilson & Golonka, 2013). As such, not only commonly acknowledged behaviors like physical activity but also activities that facilitate and eventually enhance cognitive and the central nervous system's functions may positively influence aspects that are relevant for the normal population as well. Those aspects include general well-being, health (McMorris, 2020; Pinna & Edwards, 2020; Schulz & Vögele, 2015) and performance in every-day activities like car driving (Lochner & Trick, 2014). Even though this thesis investigated the upper limits and achievements of the human brain its results may also augment the findings of the lower limits approach which investigated neuropsychological patients to show the anatomy and functionality of distinct brain structures (Damásio et al., 1994). Particularly, it represents that not only cognitive processes are disrupted by damaged brain areas but that these cognitive processes in healthy, elite performer's brains are conspicuous outliers compared to the normal population with widespread ramifications to different performance domains to achieve the upper limits of human brain performance like playing soccer on an elite level.

## 4.2 Limitations

Research examining cognitive functions in elite athletes often includes several limitations which also need to be acknowledged in the present thesis. Firstly, a meta-analytic review was undertaken in *Publication I* which is subject to the general limitations of meta-analyses' since they depend on the design and quality of the integrated studies. Thus, not every sport is included and potential moderator variables like socioeconomic status, physical fitness level, previous exposure to elite sport and high-speed video games have not been examined (*see Publication I).* The cognition-motor and cognition-success domain, especially *Publication III and IV* include differing sample sizes relating to the physiological and cognitive performance measures leading to a decreased statistical power with increased confidence interval lengths. Unfortunately, it is not always possible to gather totally equally distributed data when handling large sample sizes especially in the setting of elite soccer where several influences like illness, injuries or other absence reasons exist. Further, most of the analyzed physiological tests of the cognition-motor domain were soccer-unspecific resulting in a decreased ecological validity. A similar aspect also needs to be considered for the cognition-success investigation of *Publication IV*. Although multidisciplinary and multiphasic performance data were analyzed, the whole complexity and multifaceted demands of team sports like soccer were still not represented holistically as technical, tactical and psychological skills were not included. While previous research proposes the relevance of the analyzed performance parameters it is also possible that other measures potentially relating to success in soccer were not included. Again, like in *Publication I* no control groups matched in age- and fitness level were integrated and the game time was based on varying numbers of three to eight games due to the stoppage of the matches due to the corona pandemic.

In general, the results of *Publication II, III and IV* are based on correlational analysis and like with all of this analyses no absolutely conclusive inferences can be made as they are not causal in nature.

Lastly, the cognition-training study of *Publication V* is based on a relatively small sample size with no active but only a passive control group. Additionally, as transfer to cognitive functions but not the underlying neural processes were examined it cannot be excluded that other neuroplastic adaptations occurred (e.g. more efficient energy use).

## 4.3 Directions for future research

The results of this thesis indicate a high relevance of certain cognitive functions for high-performance in an elite sport like soccer. However, to provide more causal inferences for example on the cognition-motor relationship analyses of transfer effects of cognitive training on motor and physiological skills are required. It would also be worthwhile to study more complex and soccer-specific skills (e.g. technical skills in small sided games) and also specific other parameters of game success like decision-making or passing accuracy in real game situations. Concerning the identification of talent and key performance indicators, a more holistic and multidisciplinary analysis of cognition and physiological performance as undertaken in this thesis accompanied by technical, tactical and psychological skills is necessary to capture the multifaceted demands of the game.

As indicated by the present results future research should also intensify the investigation of the central nervous system which holds the key role in controlling and steering all performance related aspects. For example, some cognitive and motor functions are controlled by the same brain networks, thus one should investigate how the functionality of these networks enable the processing and execution of complex cognitive and motor activities in the first place. After this identification a more comprehensive understanding may be reached which could result in the application of specific methods and tools to optimize the functionality of these networks. Part of this knowledge is already present and some tools like neurofeedback applications already exist, but that does not yet suggest a systematic use. As stated in the beginning of this thesis the human brain is the most sophisticated system of the known universe. Thus, researchers and practitioners alike are required to also create sophisticated methods and tools to enhance the brain's function. Related to the common concept of the minimal effective dose in exercise science, the goal concerning those training tools could be termed as minimal sophisticated level, meaning that the tool does not need to be highly sophisticated per se only to mirror the brain but it needs to be so sophisticated that it is able to evoke improvements of the brain. A first example of such a more sophisticated tool is a computer based game grounded on the "FAST" principles representing flexible, adaptive and synergistic training of executive functions which has been shown to effective (Almquist et al., 2019)

Moreover, transfer effects and efficacy of cognitive training tools are commonly examined by using cognitive measurements like in *Publication V*. However, even if certain transfer effects would occur no information on the underlying neural adaptations enabling this transfer would be available. Other research areas for example showed the specific adaptations of the brain called myelination which basically means that a higher myelinization-degree results in higher cognitive processing speed (Fields, 2015; Forstmann et al., 2012; Madsen et al., 2010) and better motor performance (Roberts et al., 2013). Thus, by considering these neuroplastic changes required for every transfer effect of training programs (Long & Corfas, 2014), it might be possible to reverse-engineer the positive training adaptations all trainings aim to evoke. Specifically, one might investigate how the process of myelinization may be optimized and accelerated for example by applying the principles of enriched environment learning (Fields, 2015; Nithianantharajah et al., 2006)

## 4.4 Concluding remarks

Almost two centuries after the examinations of lower limits and abnormalities of the human brain in neuropsychological patients an opposing line of research has emerged which focuses on the brain's upper limits and possibilities in high-performance environments like elite soccer. A lot of research has been conducted in this domain with a recent focus on the contribution of cognitive functions to this high-performance aiming to unravel underlying mechanisms and relationships. My own results along with previous studies propose the crucial relevance of certain cognitive functions for the performance domains of *cognition-expertise, cognition-motor, cognition-cognition, cognition-success* and *cognition-training* altogether hinting at the central nervous system's key role in steering and controlling all performance areas. Based on the present thesis one might assume that one of the next steps in the research on cognitive functions in high-performance athletes should be to further investigate the underlying neural processes with the overall goal to make use of them for the creation of sophisticated cognitive training tools and methods. Although this endeavor includes some complicated challenges it is a worthwhile path, to provide a holistic theoretical framework of cognition functions and its practical applications in elite sports.

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# 6 Appendix

**Appendix I:** ***Publication I***

# Measurement of cognitive functions in experts and elite athletes: A meta-analytic review

**Reference:**

Scharfen, H. E., & Memmert, D. (2019). Measurement of cognitive functions in experts and elite athletes: A meta-analytic review. *Applied Cognitive Psychology.*

## ABSTRACT

An extraordinary physiological capacity combined with remarkable motor control, perception, and cognitive functioning is crucial for high-performance in sports. Tests that assess the physical abilities are already well established. Moreover, a growing area of research evolved in the recent past that is particularly concerned with the basic cognitive functions by means of neurocognitive tests in experts and elite athletes. The aim of this meta-analysis (k = 19) is to quantify differences among experts and nonexperts as well as elite athletes and non-elite athletes. In addition, it aims to assemble and compare previous research and analyze possible differences in cognitive functions depending on age, skill level, and used cognitive tasks. Overall, the mean effect size was small to medium (r = 0.22), indicating superior cognitive functions in experts and elite athletes. The factor of skill definition significantly differentiates the cognition–expertise relationship. In contrast, differences in age groups and cognitive areas appeared but were not significant. Future research should prefer the elite rather than the expert definition and distinguish between high-performance and amateur athletes. Furthermore, the findings suggest that it can be beneficial for coaches and sport clubs to integrate cognitive tests as an additional tool for scouting and for optimizing the athletic development of their players.

*Keywords:* age groups, cognitive areas, cognitive functions, elite athletes, experts, high-performance

## INTRODUCTION

The majority of top-class sports require an extraordinary physiological performance combined with remarkable motor control, perception, and cognitive abilities. Especially in team sports, players have to process an overflow of information in a short time and under psychological pressure. The perceived situational signals thus function as a basis for their decisions, which must be fast, accurate, and reflected depending on the demands of the game (Stratton et al., 2004). The underlying mental construct is called perceptual-cognitive skills, which refer to the abilities to identify and perceive environmental information (Roca et al., 2013). This information is integrated into the existing knowledge and enables the selection and execution of appropriate responses. The perceptual-cognitive skills are the abilities to perceive surroundings and to utilize this perception to make an optimal decision for the following actions which directly influence the game outcome in team sports.

Previous research mainly focused on the expert performance approach (Ericsson, 2003), in which athletes were examined in a sport-specific or ecologically valid context (for review, see Mann et al., 2007). Studies with this approach primarily aim to investigate eye movements, gaze behavior, declarative memory, attention and attention allocation, anticipation and decision making through sport-specific stimuli regarding expert-novice differences. The focus of these studies is on the examination of parameters that represent the direct interaction between the athlete and his specific environment. One outcome revealed that experts outperform non-experts in perceiving and responding to sport-relevant signals. The superior response accuracy and the response time in perceptual-cognitive tests for experts proved these findings (Abernethy, 1990; Helsen & Starkes, 1999; Mann et al., 2007; Wright, Pleasants, & Gomez-Meza, 1990). Furthermore, previous research confirmed that expert athletes have a different gaze behavior compared to non-expert players, as they have less eye fixation points but focus on them for a longer time (Helsen & Starkes, 1999; Mann et al., 2007; Savelsbergh et al., 2006; Savelsbergh et al., 2002). Notably, the type of sport, research paradigm and stimulus strongly influenced the measurement of these different perceptual behaviors (Mann et al., 2007).

Another approach, known as the cognitive component skills approach (Nougier, Stein, & Bonnel, 1991), investigates the relation between sports expertise and performance in standardized cognitive tests that are assumed to be relevant for the cognitive requirements of competitive sport. In contrast to the expert performance approach the cognitive component skills approach examines general cognitive functions such as cognitive flexibility, working memory and inhibition (Nougier, Stein, & Bonnel, 1991; Voss et al. 2010). Since the majority of the previous research—and in particular the expert performance approach—precisely investigated visual search behavior and gaze behavior as well as decision making and reaction times, the cognitive component skills approach and the cognitive functions are of primary interest in this meta-analysis.

While the cognitive component skills approach denounces the lack of environmental complexities that create superior expert performance (Ericsson, 2003), we consider this approach as important for measuring and depicting basic cognitive skills linked to competitive sport training (Voss et al., 2010). Until now, studies which can be aligned to the cognitive component skills approach provided contradictory findings (see a more detail description of each study in the Appendix). On the one hand some studies support the notion of superior cognitive functions in elite or expert athletes (e.g. Vestberg et al., 2012; Verburgh et al., 2016; Huijgen et al., 2015; Lundgren et al., 2016) while on the other hand some studies did not show any differences in cognitive functions (e.g. Furley & Memmert, 2010; Heppe et al., 2016). Therefore, this meta-analysis should also work out the contradictory findings by depicting and interpreting the current state of literature.

Following the call of Voss et al. (2010) several studies were carried out by various research groups to investigate higher-level cognitive tasks such as executive functions. These studies are also included in this meta-analysis. Moreover, their results are important for the cognitive component skills approach as these executive functions have not been examined systematically before. Additionally, some studies were conducted which followed the call of Furley & Memmert (2011) to control several potential confounding variables (e. g. Huijgen et al., 2015). Therefore, the current work differs from the paper of Voss et al. (2010) because it (i) incorporates results of novel studies examining executive functions, (ii) investigates the difference between skill aligning by means of the expert vs. elite definition, (iii) studies variances between differing measures of cognitive functions and ages.

Cognitive functions cannot be clearly separated from perceptual abilities, as they are a decisive part of perception (Bruce, Green, & Georgeson, 1997). Hence, some perceptual functions are included. Even though most perceptual skills are excluded, the areas of cognitive functions examined in the individual studies are still very heterogeneous. However, a meta-analytic approach also offers the possibility to examine the influence of potential moderators of cognitive component skills studies, since part of the heterogeneity of the results may result from variables that are either not controlled in certain studies or do not have a sufficient sample size within-study to achieve statistically significant effects. Therefore, a meta-analytic approach also offers the possibility to examine the influence of potential moderators of cognitive component skills studies. Contrary results may occur due to different methodological factors, such as laboratory tasks for measuring facets of cognition, participants’ sport or level of expertise (Nougier et al., 1989).

In the current study, we attempt to review the results of the different cognitive paradigms used with the cognitive component skills approach. Therefore, the cognitive measures were divided into three groups which related to the tasks used in the existing literature and to the paradigms that could be grouped. By means of this subdivision the validity of aggregating their individual measures could be conserved. The categorizations were determined from the description of neuropsychological tests in Lezak, Howieson, and Loring (2004) and previous literature on cognition and perception. This procedure resulted in three groups of dependent variables. Firstly, the executive functions (EF) which describe the cognitive processes that regulate thought and action, especially in non-routine situations (Friedman, 2006), further subdivided into core EF (CEF): working memory, cognitive flexibility and inhibitory control as well as higher-level EF (HEF) involving reasoning, problem solving and planning. At some point HEF are called fluid intelligence synonymously (Diamond, 2013). Regarding these top-down processes it is important to know that they mature at different ages, as they are dependent on different prefrontal structures. The HEF are made from the neuronal structures of the prefrontal lobes which mature slowly and reach their full capacity between 20 and 29 years of age (De Luca, 2003 & Luciana et al., 2005). In contrast to HEF, CEF develop their total capacity earlier in the lifespan, most often before early adolescence (Crone, 2006). The second sub-area includes the visual-perceptual functions consisting of peripheral awareness and attention window, visual orientation and attention ability, perceptual load, multiple-object-tracking (MOT) as well as scanning ability. Finally, cognitive processing speed, decision-making, short-term memory (pattern recall included), mental rotation, anticipation and concentration are grouped into the third sub-area, called other cognitive functions.

The complexity of high-level sports is depicted in the heterogeneity of previous research (Mann et al., 2007; Voss et al., 2010). The main aim of this current meta-analysis is to combine previous findings from research into cognitive abilities in athletes of varying performance levels – from non-elite to elite and non-expert to expert – followed by comparing functions with regard to cross-sectional study designs. Additionally, this meta-analysis urges the analysis of the possible difference in cognitive functions between adolescents and adults. Lastly, a further aim of this study is to deliver an overview of the investigated areas involved in the respective cognitive functions.

## Methods

**Search Strategy.** The literature search was conducted by following the PRISMA recommendations for reporting findings of meta-analysis (Liberati et al., 2009), i.e. focusing on the online databases PubMed and google Scholar. The search included three groups of search terms related to: 1) the outcome (perceptual-cognitive abilities OR executive function OR cognitive function OR working memory OR decision-making); 2) the athlete's skill level (professional OR elite OR high-performance OR experts OR highly-talented); and 3) the exclusion parameters (NOT disability NOT concussion NOT disease NOT return-to-play NOT patient NOT education NOT clinical NOT impairment NOT longitudinal). These selection criteria were chosen to find all relevant cross-sectional studies dealing with the defined range of cognitive functions in the population of elite athletes and expert performers. The periodic searches of the online databases lasted until the end of February 2018. In addition to the database search, further studies were searched manually via cross-references of other studies for their inclusion. The studies were weighted individually depending on their sample size.

**Selection Criteria.** Full-text articles with versions available in English and publication date before February 2018 were eligible for inclusion in this meta-analysis. Studies were only included if they: 1) examined active athletes; 2) tested a specific sport type or group of sports; 3) stated a specific expertise / competition level; 4) stated the age of the participants; 5) used a cross-sectional design; 6) employed at least one test of cognitive functions; 7) examined differences of elite / experts and lower than elite players / novices. Furthermore, studies were excluded if they: 1) used a clinical study design; 2) did not have a sport-relation; 3) only investigated vision or gaze behavior; 4) used a longitudinal design (e.g. with an intervention); 5) only used verbal reports as the measurement of cognitive functions; 6) examined coaches or retired athletes as participants; 7) did not use a cognition measurement that is separated from motor components (except clicking on a keyboard); 8) only used the investigation to assess the reliability of a specific test; 9) solely measured motor inhibition or simple reaction time; 10) only examined correlations and 11) did not have a control group. These searches yielded 3092 potentially relevant articles. After investigating these articles and excluding those which are irrelevant, we identified 19 studies that met all the inclusion criteria. A PRISMA flow diagram of the selection process is provided in Figure 1. Each study and the included measures for reference information, methodological characteristics and results were coded. Across those studies, there were 22 independent samples, with a total sample size of 1585 participants and 22 independent effect sizes, with a total of 6.02 effect sizes.

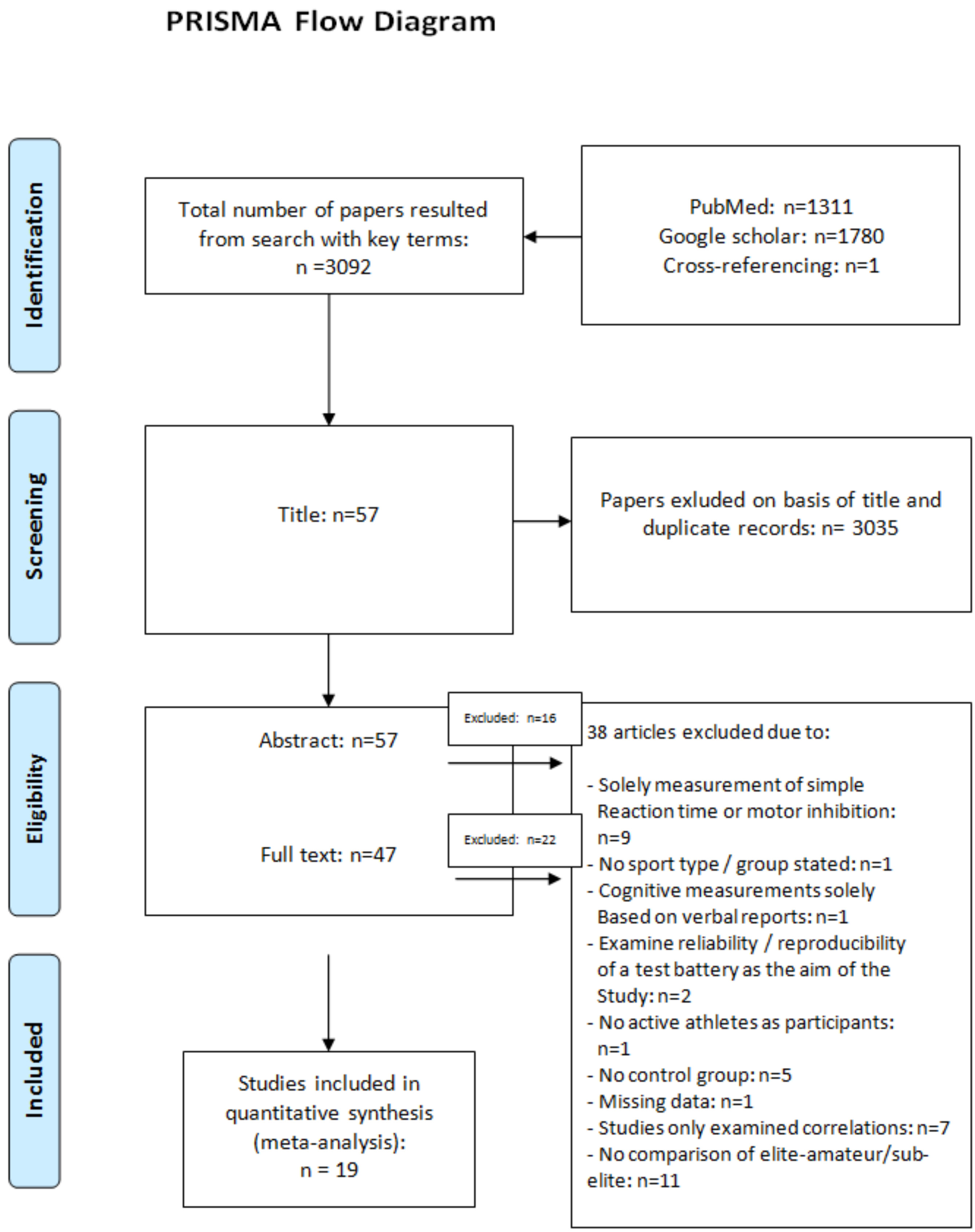

*Figure 1.* PRISMA flow chart of the literature search

**Effect sizes and moderator variables.** Correlation between competition level/ expertise and performance on the cognitive tests was used as the measure of effect sizes.

Effect size estimates, r, and overall mean r were calculated for each dependent variable while not mentioning the effect size. These effect sizes were calculated by using Comprehensive Meta-Analysis software package, Version 2 (BioStat, Englewood, New Jersey). Every effect size was consequently weighted by following the recommendations of Ellis (2010). Furthermore, statistical significance was assessed by converting the results into a z score and calculating mean r, 95% confidence intervals (CI) around the mean to determine whether effects were significantly different from zero and comparisons of the mean r between levels of moderator variables (Cooper & Hedges, 1994). Additionally, omnibus test statistic Q was computed to determine the variability in the distribution of effect size estimates (Ellis, 2010), followed by the calculation of heterogeneity indicating whether Q exceeded the upper limit critical value of $\chi2$ at $k–1$ degrees of freedom (Cooper & Hedges, 1994). Furthermore, the moderator variables age (youth: <18 years of age vs. adults: >18 years of age), skill definition (elite vs. expert) and tested cognitive areas (executive functions vs. visuo-perceptual functions vs. other cognitive functions) were examined according to the recommendations of Lipsey & Wilson (2001) using the analog to the ANOVA in order to analyze heterogeneous distributions. Cohen’s recommendations for correlational effect sizes (Cohen, 1988; Ellis, 2010), which state that values of .10, .30 and .50 represent small, medium and large effect size estimates, is used here as the basis for every reported qualification of the magnitude and effects of the estimated effect size. Finally, we checked if the meta-analysis may be influenced by a publication bias using a trim and fill procedure by Duval & Tweedie (2000). Resulting from an uneven publication of statistically significant and non-significant results or even exclusion of studies that fail to find statistically significant results, meta-analyses do not always reflect the current research situation. Therefore, the possibility of a publication bias had to be tested and – if existing – the effects should be adjusted. In our sample, published studies with higher standard errors often show effects larger than the ‘true’ theoretical population effect, while studies with the lowest standard errors show effects that comply with the population effect. As a result there may be a biased overestimation of the population effect as there seems to be a lack of studies with a high standard error and lower estimated effect size. The trim and fill procedure (Duval & Tweedie, 2000) which was used is a non-parametric statistical technique that examines the symmetry and distribution of effect sizes against the inversion of variance or the standard error. Therefore, as a first step, the number of studies that may be missing due to a possible publication bias is estimated. Afterwards the procedure is used to calculate hypothetical effects for studies that might have not been published. Finally, the average effect size and confidence intervals including these hypothetical results can be estimated. In this case the initially calculated overall effect size had to be adapted according to the results of the trim and fill procedure that indicated a potential lack of three studies.

## Results

As mentioned previously, 22 effect sizes were calculated across 19 studies with a total of 1585 participants. Each study was coded and weighted individually according to Ellis (2010). The meta-analytic average correlation between performance on cognitive tests and expertise / elite level athletes was depicted as a small mean effect size of 0.291 (95% CI -0.25 0.33), which was significant (*z* = 6.684, *p* < .05). The distribution of the effect sizes was heterogeneous *Q* (1) = 41.511 *p* < .05. Figure 2 shows that all correlations between performance on cognitive tests and expertise / elite level athletes are positive: expertise and elite level sports were associated with high levels of performance on cognition tests. However, as indicated by the *Q* statistic, which specifies the percentage of the between-studies variability in effect sizes that is caused by heterogeneity rather than random error, a high degree of heterogeneity in the effect sizes, *Q* = 41.511 appeared. Therefore, we examined the source of this heterogeneity through the moderator analyses explained in the following.

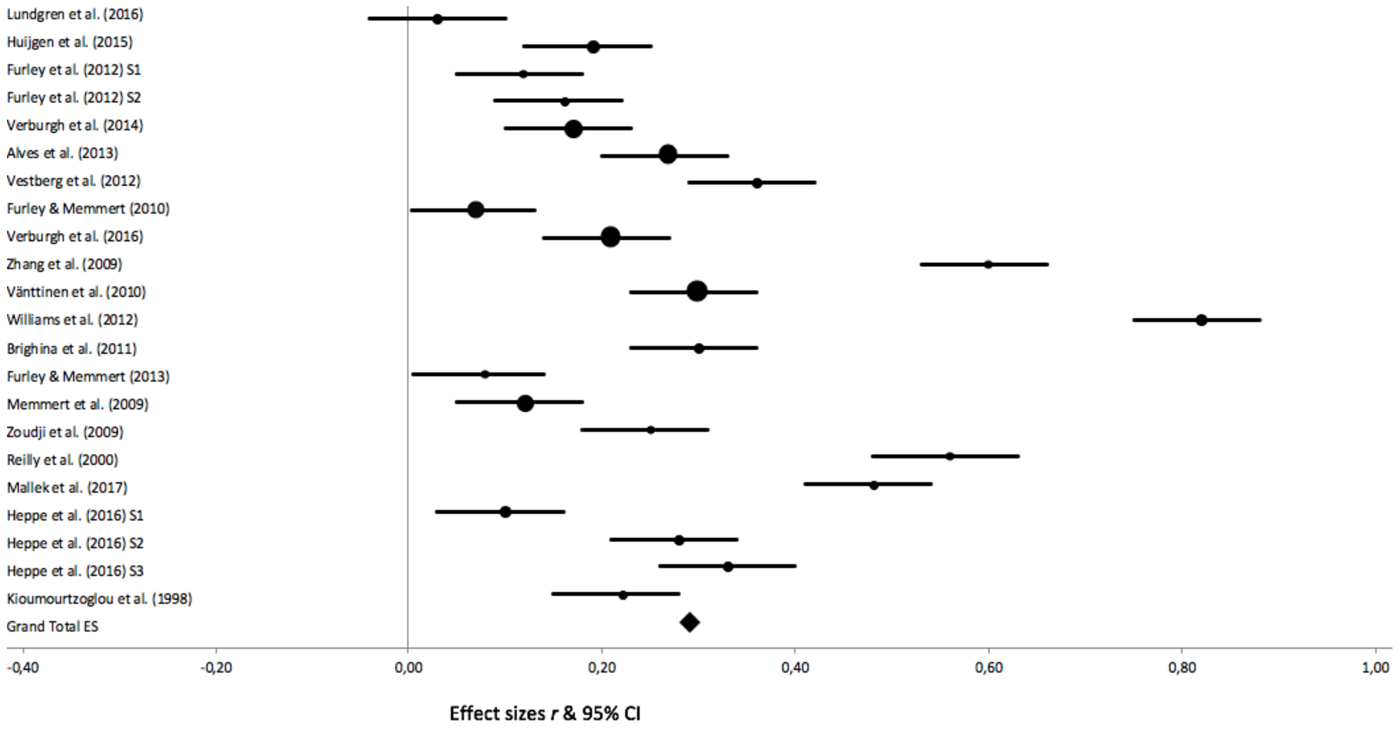

*Figure 2*. Effect sizes *r* and confidence intervals of each independent sample

## Results of moderator analyses

***Skill Definition.*** In some studies (e.g. Memmert, Simons, & Grimme, 2009) high-performance athletes are defined by the amount of training according to Ericsson et al. (1993), who defined athletes with at least 10.000 hours of deliberate practice as “Experts” in their fields. In contrast to this approach most of the studies categorized high-performance athletes regarding their competition level (i.e. elite vs. sub-elite or non-elite). The effect of skill definition was significant, $Q(1) = 7.41$, $p < .05$.

**Age**. The age of the participants was of primary interest as a potential moderator to investigate whether age (adolescents vs. adults) influenced the skill-based cognitive performance. Nevertheless, the difference was not significant, $Q(1) = 0.61$, $p > .05$. Examined cognitive subareas. Researchers have questioned the degree up to which various examined cognitive subareas adequately differentiate between elite, expert and non-elite, non-expert and whether there are any differences in the outcome. The effect of the examined cognitive subareas approached but slightly lacked significance, $Q(1) = 5.89$, $p > .05$.

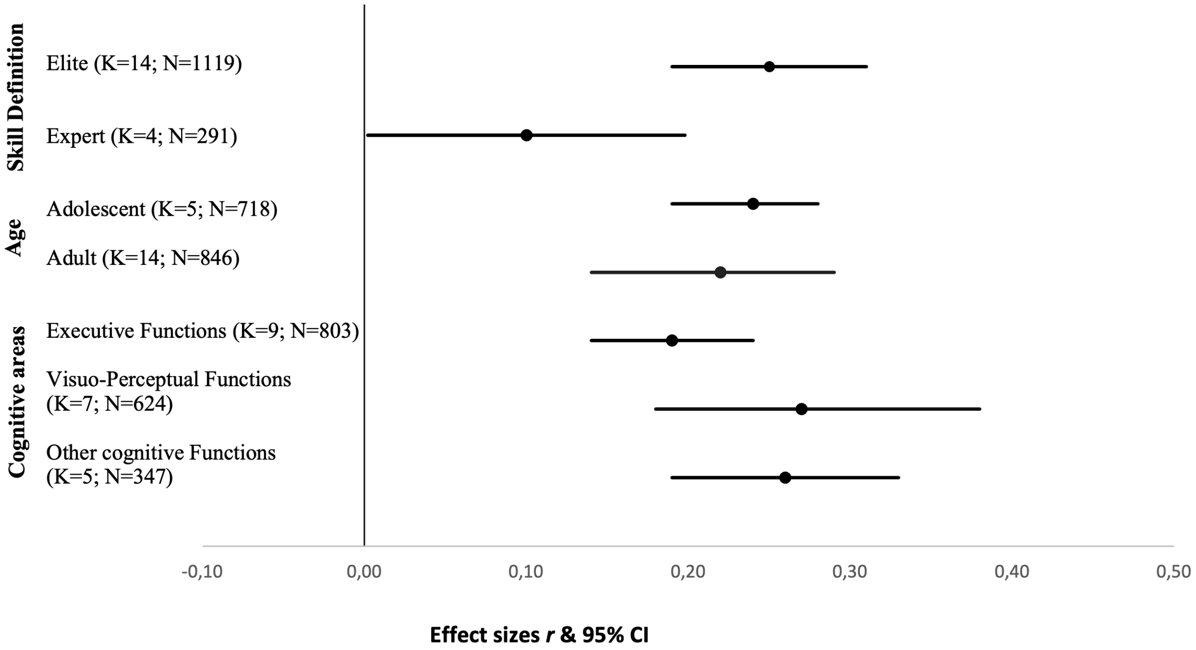

*Figure 3.* Effect sizes *r* and confidence intervals of moderator variables (*K*= number of studies, *N*=number of participants)

# DISCUSSION

The purpose of this meta-analysis was to provide a quantitative synthesis of the research on cognitive expertise in sport, especially in experts and elite-athletes compared to non-experts and non-elite-athletes. We aimed to assess the moderating effects of different ages, skill definitions and examined cognitive subareas. The diverse research on sports expertise is divided into two perspectives: The expert performance approach investigates the athlete in a sport-specific, or an ecologically valid context (Mann et al., 2007; Starkes & Ericsson, 2003). In contrast, the cognitive component skills approach examines the relationship between basic measures of cognitive abilities and sports expertise (Nougier et al., 1991; Starkes & Ericsson, 2003). This study quantitatively reviewed the current literature related to the category of the cognitive component skills approach.

All in all, we found a small-to-medium sized effect for the overall elite and expert population, suggesting that despite the heterogeneity of effects found in different studies, the overall average effect is statistically significant in favor of experts and elite-athletes compared to non-experts and non-elite-athletes. This is in line with previous meta-analyses by Mann et al. (2007) and Voss et al. (2010). Even though most studies show small positive effects, they are often not statistically significant. We were able to aggregate the effects across these studies with the aim to increase the statistical power that was lacking in many of these studies due to small sample sizes of elite and expert groups. The different categorization of high-performance athletes or skill level in terms of the "elite" or "expert" definition influences the outcome. This indicates, that a differentiation of high-performance athletes based on accumulated hours or years of training as Ericsson (1993) suggests, may not be precise enough to distinguish between high-performance and semi-professional athletes. The problem in this approach is that hours and years of practice can strongly differ among athletes, as the theory of deliberate practice postulates (for a review, see Macnamara et al., 2016). In contrast to this approach, the classification of elite-athletes based on their current level of competition or based on the division they are currently playing in at least eliminates the probability of falsely aligning athletes to a high-performance group. Nevertheless, this grouping may not be totally valid because it may occur that, regarding to their capabilities, athletes from division 3 could be able to play in division 1, too, or vice versa.

Moreover, the difference among the age groups was not significant, but slightly favors the adolescent age group compared to the adult group. By linking these findings with the different maturation time points of different cognitive functions, the conclusion could be drawn that the superiority of experts and elite-athletes compared to non-experts and non-elite-athletes is not constrained to individual cognitive functions but rather accounts for most of the tested cognitive functions. This is the first study to our knowledge that investigates the difference among these age groups.

The last moderator variable slightly lacks statistical significance in terms of heterogeneity due to variability of the data. This is revealed via different examined cognitive areas which have been grouped into (1) executive functions, (2) visuo-perceptual functions and (3) other cognitive functions. As previously shown, the reviewing examination of executive function studies is the first of its kind summarizing various studies. Given the findings of most of the individual studies, in which executive functions could separate elite-athletes and experts from non-elite-athletes and non-experts, we believe that it would have been a more statistically powerful and informative comparison, if a larger sample size had been given. In terms of visuo-perceptual functions the small-to-medium effect is in line with previous meta-analyses (Mann et al., 2007; Voss et al., 2010), although the underlying tests of the visuo-perceptual functions analyzed in the current study differ from those analyzed in the previous meta analyses. The largest effect is revealed for cognitive areas of other cognitive functions, which is a mixed group of different cognitive abilities (e. g., cognitive processing speed, decision-making and short-term memory). In this case it is important to note, that, although this is already a subgroup of the general term “cognitive functions” the included functions are still very heterogenous.

Additionally, given the literature showing that aerobic exercise enhances cognitive and neural plasticity (Colcombe & Kramer, 2003; Kramer & Erickson, 2007), future research should also include a group of high-fit age-matched controls. Since the cognitive benefits associated with aerobic exercise have been connected primarily to higher-level cognition, such as executive function measures, it could be assumed that aerobically fit individuals with no competitive sport training experience would not show the executive functions or other cognitive function benefits compared to elite-athletes.

Furthermore, previous literature has described cognitive skills which characterize experts and elite-athletes with a ‘hardware vs. software analogy’. In this analogy, hardware represents aspects of the central and peripheral nervous system and software represents a sport-specific skill set that is acquired through practice (Helsen & Starkes, 1999; Starkes, 1987). The sport-specific skill tests largely covered sport expertise effects, the software domain, compared to central and peripheral nervous systems, the hardware domain. The division into soft- and hardware unravels the nature vs. nurture conflict. Additionally, this ‘hardware vs. software analogy’ as well as the nature vs. nurture conflict is also related to a possible selection process for elite-athletes. On the one hand it could be possible to filter the high-performance athletes who have superior cognitive functions from the beginning, which would support the nature standpoint. On the other hand, specific training methods, for example deliberate practice, could create athletes who are cognitively superior to athletes who do not have access to these training methods. This would represent the nurture viewpoint. Nevertheless, the implication that the hardware is innate and therefore not malleable can be considered as critical. Therefore, the cognitive component skills approach, as well as the growing area of sport-neuroscientific research views sport-specific training as a tool that affects and causes experience dependent brain plasticity. Moreover, it is assumed that cognitive training results in more efficient brain networks (both general and sport-specific), for example, due to higher degrees of myelination in the nervous system. A higher degree of myelination speeds up the transfer of information among nerve cells (Mount & Monje, 2017; Wenger et al., 2017; Long & Corfas, 2014) which results in unique cognitive skill profiles. This would support the notion of the nurture standpoint like Ericsson postulated (Ericsson, 1993).

However, future research consisting of longitudinal studies should examine changes in cognitive functions (representing software) as a function variable of experience (e.g. years of training, type of training, training intensity and duration, etc.) compared to changes in brain structures – e.g. myelin – (representing hardware) in elite-athletes. This would enlarge the existing knowledge regarding the nature vs. nurture and software vs. hardware question. In addition, a caveat of these results is that sport training is just one of several mechanisms for athletes to show enhanced cognitive skill performance. It is possible (and very likely) that factors such as genetics or socioeconomic status also matter in the cognitive performance differences seen here. These questions could not be answered in the present study and thus could be an inspiration for longitudinal studies of athletic training. Generally, it will also be important for future research to investigate whether enhanced cognitive skills due to sport transfer to other sports (cognitive cross training) influence tasks of every-day living such as paying attention while driving a car or being productive in a noisy workplace.

According to these variables like socioeconomic status the current work includes an important limitation. It could be possible that this pattern of results occurs due to confounding variables which were not examined in the individual studies. The influence of playing video games on cognitive functions as Green & Bavelier (2003) showed could be one of these influencing variables. Therefore, these results should be interpreted with caution and as mentioned previously, future research should incorporate these potential confounding variables.

Similarly, meta-analyses can be used not only to examine the strength of the relationship between two variables and to identify variables that moderate this relationship but also to empirically evaluate theories (for a review, see Chan & Arvey, 2012). The present meta-analysis is limited by the studies having been reported to date. For example, not every sport is represented in the meta-analysis. Additionally, there are some criticisms that question the applicability and validity of current cognitive test batteries (Cremen & Carson, 2017). However, assuming that appropriate inclusion criteria and systematic procedures are used, meta-analyses should provide the most precise information about the strength of the investigated effect and about the accuracy of the theory in question. Moreover, meta-analytic results are more generalizable than the results of a single study and thereby contribute to scientific progress in an area.

## Conclusion

In sum, we found that experts and elite-athletes do have superior cognitive functions compared to non-elite-athletes and non-experts, although this effect is only small-to-medium sized. We also found that there was no significant difference in terms of age groups but in terms of skill definition favoring the elite definition. A large but statistically non-significant difference was found for the cognitive areas with the largest effect in the area of other cognitive functions (processing speed, decision-making, short-term memory (pattern recall included), mental rotation, anticipation).

These findings are important from both a theoretical and a practical perspective. On the theoretical level future research should rather focus on the elite than on the expert definition by using current performance levels as the tool for categorization and distinguishing between high-performance athletes and semi-professionals or amateurs. From a practical perspective, knowledge about the contribution of cognitive functions linked to the already proven superior perceptual functions to elite performance may help sport clubs to scout for talents and new players in a more effective and comprehensive way. This sophisticated scouting system could be created by adding a cognitive scouting or test tool to the categories of technique, athleticism and tactics. Adding the cognitive tool is backed up by studies which report a high link and overlap between cognitive functions and game intelligence, which is crucial for success in elite sports and still hardly measurable (e.g. Vestberg et al., 2012). Additionally, this knowledge could be used by coaches and scientists to test athletes not only physically but also on the cognitive domain and therefore further individualize training programs to enhance important cognitive functions and reduce (psychological) weaknesses to guarantee a holistic and sophisticated development of athletes. These important cognitive functions could be further profiled and predicted by creating specific cognitive portrait for (1) various sport types, (2) various stages of age in specific sport types, (3) specific positions in specific sport types. By doing so, baseline and reference values could be created for an augmented comparison of current training status, weaknesses and strengths and for precise distinction distinguish between possible elite and sub-elite players.

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**Appendix I.I** Detailed information of studies included in Meta-Analysis

| Authors | Study Number | Groups/ Sample Size/ Gender | Age (in years) | Sport | Level of Expertise [Years of Practice] | Cognitive Tests [Other Tests] | Examined Cognitive Areas [Other Examined Areas] | Results | Effect size *r* |
|---|---|---|---|---|---|---|---|---|---|
| Lundgren et al. (2016) | Study 1 | Total: n=46 (male)<br>High Division (HD): n=28<br>Low Division: (LD) n=18 | *M*=23.7 *SD*=4.96 | Ice hockey | HD: Highest national level (Swedish Hockey League level A)<br>LD: Third highest Swedish Hockey League (Division 1 level B) | Design Fluency Task (DF, D-KEFS)<br>Trail-making task (TMT)<br>[Assessing of game intelligence by experts]<br>[Assessing of performance] | General executive functions<br>Cognitive flexibility, visual scanning, split attention<br>[game intelligence]<br>[on-ice performance] | HD players *sign*. better than standardized sample but not than LD players<br>*No sign*. difference between HD, LD or compared to standardized sample<br>Correlations:<br>- *No sign*. correlation between DF scores & plus/minus statistics; age; game intelligence<br>- *Sign*. correlation between DF scores & plus / minus statistics<br>- position & DF: center forwards *sign*. better than other level A players | 0.03 |
| Huijgen et al. (2015) | Study 1 | Total: n=88 (male)<br>Elite group: n=47<br>Sub-elite group: n=41 | *M*= 15.48 *SD*=0.90<br>*M*=15.15 *SD*=1.18<br>Range: 13-17 | Soccer | Dutch youth academy, top 0,5% of all players)<br>[*M*= 9.8, *SD*= 0,8]<br>Dutch, top 12,5% of all players<br>[M= 9.3, SD= 1,5] | Trail Making Test (TMT-A)<br>Stop -Signal Task (MRT)<br>Backward Visual Memory Span<br>Stop-Signal Task (SSRT)<br>Trail Making Test (TMT-B) | *Low level functions*: Visual perceptual ability<br>Motor Inhibition<br>*Higher level functions*: Working memory<br>Inhibitory control<br>Cognitive flexibility, | *Significant* differences:<br>- Academic level<br>- Weekly training hours<br>- Higher level EF: better inhibitory control, cognitive flexibility, metacognition<br>(metacognition not significant any more when training hours | 0.19 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Design Fluency Task (DF, D-KEFS) | visual scanning, split attention<br>Metacognition (working memory, inhibitory control, cognitive flexibility, creativity, planning) | are taken into account)<br>*Non-significant* differences:<br>- Lower level functions<br>- Working memory | |
| Furley et al. (2012) | | Total: n= 65 (male & female)<br>Expert team sport players: n=32 | | Basket ball, Soccer | Amateur to semiprofessional level<br>[at least 10 years of deliberate practice] | General Perceptual Load task | Perceptual Load | *No sign*. expert-novice differences | |
| | Study 1 | College students: n=33<br>Experts: n=17<br>Novices: n=18 | *M*=22.7 *SD*=6.1<br>*M*=23.1 *SD*=3.3<br>Range: 15-35 | | Experts [*M*=13]<br>Novices [*M* =0] | Soccer-specific Perceptual Load task | Perceptual Load | *No sign*. expert-novice differences | 0.12 |
| | Study 2 | Experts n=15<br>Novices n=15 | *M*= 24 *SD*=3.2<br>*M*=21.8 *SD*=2.6<br>Range: 15-38 | | Experts [*M* =12.6]<br>Novices [*M* =0] | | | | 0.16 |
| Verburgh et al. (2014) | Study 1 | Total: n=126 (male)<br>High Division (HD) group: n=84<br>Low Division (LD) group: n=42 | *M*=11.9 *SD*=2.2<br>*M*=11.8, *SD*=2.3<br>Range: 8-12 | Soccer | HD= elite (Dutch youth academy)<br>[*M*= 6.7, *SD*=1.4]<br>LD= amateur (Dutch, average league level: 6, range from 4 to 9)<br>[*M*= 5.1, *SD*=1.5] | Stop Signal task (SSRT)<br>Attention Network Test<br>Visuospatial working memory task<br>[Full-scale IQ estimation]<br>[Physical activity estimation] | Motor Inhibition<br>Alerting & orienting attention, Executive network & attention<br>Working memory: Central executive & visuospatial sketchpad<br>[Wechsler Intelligence Scale for Children III]<br>[questionnaire: amount of | HD *significantly* superior to LD<br>HD: *non-significant* slower mean reaction time on go trials than LD<br>HD: *significantly* larger MRT-gain in HD than LD<br>*No sign*. difference: orienting attention & executive attention | 0.17 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | physical activity] | *No sign*. differences | |
| Alves et al. (2013) | Study 1 | Total: n=154 (male & female)<br>Adult players: n=30 Male<br>Female<br>Junior players: n=57 Male<br>Female<br>Non-athlete adult control: n=27 Male<br>Female<br>Non-athlete junior controls: n=40 Male<br>Female | *M*=24.8 *SD*=4.4<br>*M*=20.5 *SD*=1.2<br>*M*=17.5 *SD*=0.9<br>*M*=16.2 *SD*=1.0<br>*M*=23.3 *SD*=3.0<br>*M*=21.5 *SD*=1.5<br>*M*=17.3 *SD*=1.1<br>*M*=16.4 *SD*=1.5 | Volley ball | Elite players: Brazilian Center for Development of Volleyball<br>Non-athletes: Brazilian universities & schools | Task switching Test<br>Stopping Task<br>Visual short-term memory Test<br>Useful field of view Test<br>Flanker test<br>Change detection | *Higher-level functions*: Cognitive shifting<br>Motor inhibition<br>*Memory*: Visual short-term memory, Visuo-spatial attentional processing<br>Breadth of visual attention<br>Selective attention<br>Visual attention & memory | Athletes *sign*. faster than control on single task<br>Control *sign*. faster on go, athletes *sign*. faster on stop condition<br>Control: adult *sign*. faster than junior on stop; junior athletes *sign*. faster than junior control on stop; athletes *sign*. higher probability to stop than control<br>No *sign*. difference in visual short-term memory, visuo-spatial attentional processing, breadth of visual attention, selective attention<br>Athletes *sign*. faster than controls in visual attention & memory | 0.27 |
| Vestberg et al. (2012) | Study 1 | Total: n=57 (male & female)<br>High Division (HD) group: n=29<br>Lower Division (LD) group: n=28 | *M*=25,3 *SD*=4,2 | Soccer | HD= Swedish highest division soccer league<br>LD= Swedish 3rd national division (male) & Swedish 2nd national division (female) | Design Fluency (DF, D-KEFS) -> main test<br>Colourword interference test (CWI)<br>Trail making test (TMT) -> control tests | Metacognition (creativity, response inhibition, cognitive flexibility)<br>Cognitive flexibility<br>Scanning ability & short term memory | Cross-sectional tests: Male & female players in both groups performed *sign*. above standard population average<br>HD players *significantly* better than LD players in metacognition, cognitive flexibility (only CWI4), | 0.36 |

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| | | | | | | | | scanning ability & short-term memory<br>Prospective test: *Significant* correlation between DF & square root of points (goals & assists) | |
| Furley & Memmert (2010) | Study 1 | Total: n=112 (male)<br>Athletes: n=54<br>Non-athletes: n=58 | *M*= 24.8 *SD*=2.7 | Basket ball | Sub-elite (college students)<br>[minimum: 10 years, not below 4th highest league in Germany] | Corsi Block-tapping task | Spatial working memory span | No *sign*. expertise difference | 0.07 |
| Verburgh et al. (2016) | Study 1 | Total: n=168 (male)<br>Non athletes: n=51<br>Non-elite soccer players: n=48<br>Elite soccer players: n=69 | *M*= 10.4 *SD*=1.2<br>*M*=10.5 *SD*=1.3<br>*M* =10.6 *SD*=1.4<br>Range: 8-12 | Soccer | Non elite (regional amateur soccer clubs)<br>Elite (Dutch youth academy) | Stop Signal Task (SSRT)<br>Digit Span Forwards (of Digit Span task of WISC III)<br>Adapted version of Bergman-Nutley task (VTSM Forwards)<br>Modified version of Attention Network Test (ANT)<br>Modified version of Flanker task<br>[Wechsler intelligence scale for children III]<br>[BMI]<br>[Physical activity & sendentary behavior] | Motor Inhibition<br>*Memory*: Verbal short term memory<br>Visuospatial short term memory<br>*Attention*: Alerting & orienting attention, Executive function<br>Processing speed<br>[Full scale IQ] | Elite athletes *sign*. outperform both groups on inhibition, short term memory, working memory (only non-athletes)<br>Non elite athletes *sign*. better than non-athletes in short term and working memory | 0.21 |
| Zhang et al. (2009) | Study 1 | Total: n=37 (males & females) | | Volley ball | National top level sports university | Multiple Object | Visuospatial attention | Elite: *sign*. shorter MRT | 0.6 |

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| | | Athletes: n=17 | *M*=20.2<br>*SD*=1.9 | | [8-10 years]<br>Non-athletes | Tracking Task | | than non-athlete | |
| | | Non-athletes: n=20 | *M*=19<br>*SD*=0.8<br>Range: 18-24 | | | | | | |
| Vänttinen et al. (2010) | | Total: n=245 (male) | | Soccer | Sub-elite (regional team from Finland)<br>Sub-elite (regional team from Finland)<br>Addition of elite (U16: national team candidates, U19: national team) | Simple reaction time test (Wayne Saccadic Fixator board)<br>Peripheral awareness (Wayne Peripheral Awareness Trainer)<br>[Eye-hand-foot coordination (Wayne Saccadic Fixator board)]<br>[Hormonal analysis (study 2)] | Processing speed<br>Breadth of visual attention<br>[Maturity status of players (testosterone)] | Study 1 (cross-sectional):<br>Simple reaction time: Expertise difference only *sign*. in 16 year old group<br>Peripheral awareness: *Sign*. difference between 10-12, 14-16<br>Slightly but *not sign*. faster M(RT)<br>Study 3 (cross-sectional):<br>Simple reaction time: Sub-elite & elite players *sign*. faster than non-soccer players<br>U16 elite *sign*. faster than U16 sub-elite<br>*No sign*. difference U16 elite & U19 elite, U16 elite & U16 sub-elite<br>Peripheral awareness: *Sign*. difference between elite players & non-soccer players | 0.3 (study 3) |
| | Study 1 | Sub-elite soccer players: n=123<br>Non-soccer playing children: n=122 | Age groups 10,12,14 & 16<br>Age groups 10,12 & 14 | | | | | | |
| | Study 2 | 10,12 & 14 year old groups: n=41 | Age groups 16 (2) & 19 (1) | | | | | | |
| | Study 3 | Age group 16: n=142 (sub-elite)<br>Age group 16: n=40 (elite)<br>Age group 19: n=16 (elite) | | | | | | | |

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| Williams et al. (2012) | Study 1 | Total: n=60 (male)<br>Elite: n=48<br>Non-elite: n=12 | <br>*M*=17.8 *SD*= 1.4<br>*M*=19.8 *SD*=0.7 | Soccer | English youth academies<br>[*M*=10.4, $M_{\text{time}}$ in youth academy=7.2 *SD*=4.0]<br>Non-elite= amateur to semi-professional<br>[*M*=13.1] | Anticipation test (film-based paradigm)<br>Situational assessment (soccer action sequences different to first ones)<br>[Career Practice Questionnaire]<br>Soccer memory recall test | Ability to anticipate actions<br>Ability to assess situational information<br>[Participation history profiles]<br>Pattern recall ability | Perceptual-cognitive expertise (response accuracy): Elite scored *sign*. higher than non-elite players | 0.82 |
| Brighina et al. (2011) | Study 1 | Total: n=56 (male)<br>Volleyball-players: n=24 National<br>Regional<br>Rowers: n=12<br>Sedentary controls: n=23 | <br>*M*=26.0 *SD*=4.3<br>*M*=25.6 *SD*=3.4<br>*M*=19.2 *SD*=4.0<br>*M*=24.8 *SD*=2.5 | Volley ball, Rowing | Elite & semi-elite: Italian national level 12 & regional level 12 | Computerized version of modified Landmark task | Visuospatial attention Lateralization | RT: Elite & sub-elite volleyball players *sign*. faster than rowers & controls *No sign*. difference between elite & sub-elite volleyball players<br>Errors: Elite volleyball players: *sign*. lower number of errors compared to all other groups<br>Lateralization: Elite volleyball players: *sign*. fewer mistakes on the left compared to the right side than all others<br>*No sign*. difference in right side errors | 0.3 |
| Furley & Memmert (2013) | Study 1 | Total: n=24 (male & female) | *M*=25.25 | Handball | Experts 1 [*M*=12.21] | Computer based sport task (Exp. | Working memory | *No sign*. expertise difference | 0.08 |

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| | | Experienced handball players: n=12<br>Non-experienced: n=12 | | | Experts 2 [*M*=14.2] | 1: identify who has the ball) | | | |
| Memmert et al. (2009) | Study 1 | Total: n=120 (male & female)<br>Handball experts: n=40<br>Athletes non-team sport: n=40<br>Novice athletes: n=40 | <br>*M*=24 Range: 22-29<br>*M*=25 Range: 22-27<br>*M*=23 Range: 21-29 | Handball, Track | Experts [more than 10] | Functional field of view<br>MOT task<br>Computer-based in-attentional blindness | *Attention tasks*<br>Ability to attend objects appearing far from fixation<br>Visuospatial attention<br>Ability to notice unexpected objects when performing attention-demanding monitoring task | *No sign*. expertise / sports type difference | 0.12 |
| Zoudji et al. (2010) | Study 1 | Total: 24 (male)<br>Elite group: n=12<br>Non-elite group: n=12 | <br>*M*=22 *SD*=3.09<br>*M*=22 *SD*=2.13 | Soccer | Elite (top level team) [*M*=14.8 SD=3.7] | Decision making task (based on soccer-related situations)<br>Explicit memorization task | Decision making ability<br>Visuospatial short-term memory | Experts: *sign*. more correct responses (Response accuracy)<br>*No sign*. group or condition difference (Response consistency)<br>*No sign*. difference in response accuracy, response time | 0.25 |
| Reilly et al. (2000) | Study 1 | Total: n=31 (male)<br>Elite group: n=16<br>Sub-elite group: n=15 | *M*=16.4<br>*M*=16.4 Range: 16.2-16.6<br>*M*=16.4 Range: 15.8-16.7 | Soccer | Professional youth soccer<br>Local and school teams | Anticipation test<br>[Physiological Soccer-specific skills test] | Anticipation ability | Elite players: *sign*. better anticipatory performance (only on 1 vs 1 condition not on 3 vs 3, 11 vs 11) | 0.56 |
| Mallek et al. (2017) | Study 1 | Total: n=40 (male & female) | | Tennis | Elite | Visuo-motor | Visuospatial attention | Initiation time: | 0.48 |

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| | | Super-Experts: n=13 | *M*=22.17<br>*SD*=5.04 | | (Super-Experts = International level; Experts = good to very good in French federation's regional classification) | tracking task (VMT) | | *Sign*. difference between experts, super-experts and non-experts<br>*No sign*. difference between experts & super-exp.<br>First interception time: *Sign*. short MRT for super-experts than both other groups<br>Movement time: *No sign*. difference<br>Time-to-peak-velocity: *Sign*. better performance in super-experts than both other groups<br>Peak velocity value: *No sign*. difference<br>Distance to target analysis: *Sign*. greater distance in non-experts than both expert groups | |
| | | Experts: n=14 | *M*=21.12<br>*SD*=1.3 | | | | | | |
| | | Non-Experts: n=13 | *M*=23.89<br>*SD*=5.48 | | | | | | |
| Heppe et al. (2016) | Study 1 | Total: n=61 (male & female) | | Handball, Soccer, Volleyball | First or second division in Switzerland | Mental rotation experiment<br>d2 test | Mental rotation ability<br>Sustained attention | *Study 1*: *No sign*. difference between elite & recreational<br>*Study 2*: *No sign*. difference between elite & recreational | 0.1 |
| | | Elite: n=31 | *M*=23.2<br>*SD*=4.1<br>Range: 16-34 | | | | | | |
| | | Recreational: n=30 | *M*=21.7<br>*SD*=1.7<br>Range: 16-23 | | | | | | |
| | Study 2 | Total: n=54 (male & female) | | | First or second league in Germany | | | *Study 3*: Elite *sign*. better than recreational athletes on | 0.28 |
| | | Elite: n=27 | *M*=24.6<br>*SD*=4.0 | | | | | | |

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| | | | Range: 17-28 | | | | | sustained attention | |
| | | Recreational: n= 27 | *M*=23.9<br>*SD*=3.2<br>Range: 20-31 | | | | | | |
| | Study 3 | Total: n=52 | | | | | | | 0.33 |
| | | Elite: n=26 | *M*=21.9<br>*SD*=3.81<br>Range: 17-32 | | Soccer= 3rd national league team<br>Volleyball= first German division | | | | |
| | | Recreational: n=26 | *M*=22.0<br>*SD*=3.15<br>Range: 18-29 | | | | | | |
| Kioumourtzoglou et al. (1998) | Study 1 | Total: n =28 (male) | | Basket ball | Greece national team | Vienna test system (memory task, advanced progressive matrices test) | Memory & recognition | Elite *sign*. better in perceptual abilities (selective attention, prediction assessment) & cognitive abilities | 0.22 |
| | | Elite: n=13 | *M*=22.7<br>*SD*=1.2 | | | | | | |
| | | Controls: n=15 | *M*=21.7<br>*SD*=1.0 | | | SuperLab (sport-specfic video)<br>[Laboratory measurements] | Processing speed & motor inhibition<br>[Motor abilities] | *No sign*. difference for speed of perception or response selection patterns or memory patterns of information | |

| Authors | Study Number | Groups/ Sample Size/ Gender | Age (in years) | Sport | Level of Expertise [Years of Practice] | Cognitive Tests [Other Tests] | Examined Cognitive Areas [Other Examined Areas] | Results | Effect size *r* |
|---|---|---|---|---|---|---|---|---|---|
| Lundgren et al. (2016) | Study 1 | Total: n=46 (male) | *M*=23.7<br>*SD*=4.96 | Ice hockey | HD: Highest national level (Swedish Hockey League level A) | Design Fluency Task (DF, D-KEFS) | General executive functions | HD players *sign*. better than standardized sample but not than LD players | 0.03 |
| | | High Division (HD): n=28<br>Low Division: (LD) n=18 | | | LD: Third highest Swedish Hockey League (Division 1 level B) | Trail-making task (TMT)<br>[Assessing of game intelligence by experts] | Cognitive flexibility, visual scanning, split attention | *No sign*. difference between HD, LD or compared to standardized sample | |

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|---|---|---|---|---|---|---|---|---|---|
| | | | | | | [Assessing of performance] | [game intelligence]<br>[on-ice performance] | Correlations:<br>- *No sign*. correlation between DF scores & plus/minus statistics; age; game intelligence<br>- *Sign*. correlation between DF scores & plus / minus statistics<br>- position & DF: center forwards *sign*. better than other level A players | |
| Huijgen et al. (2015) | Study 1 | Total: n=88 (male)<br>Elite group: n=47<br>Sub-elite group: n=41 | *M*= 15.48 *SD*=0.90<br>*M*=15.15 *SD*=1.18<br>Range: 13-17 | Soccer | Dutch youth academy, top 0,5% of all players)<br>[*M*= 9.8, *SD*= 0,8]<br>Dutch, top 12,5% of all players<br>[M= 9.3, SD= 1,5] | Trail Making Test (TMT-A)<br>Stop -Signal Task (MRT)<br>Backward Visual Memory Span<br>Stop-Signal Task (SSRT)<br>Trail Making Test (TMT-B)<br>Design Fluency Task (DF, D-KEFS) | *Low level functions*: Visual perceptual ability<br>Motor Inhibition<br>*Higher level functions*: Working memory<br>Inhibitory control<br>Cognitive flexibility, visual scanning, split attention<br>Metacognition (working memory, inhibitory control, cognitive flexibility, creativity, planning) | *Significant* differences:<br>- Academic level<br>- Weekly training hours<br>- Higher level EF: better inhibitory control, cognitive flexibility, metacognition<br>(metacognition not significant any more when training hours are taken into account)<br>*Non-significant* differences:<br>- Lower level functions<br>- Working memory | 0.19 |
| Furley et al. (2012) | | Total: n= 65 (male & female)<br>Expert team sport players: n=32 | | Basketball, Soccer | Amateur to semiprofessional level<br>[at least 10 years of deliberate practice] | General Perceptual Load task | Perceptual Load | *No sign*. expert-novice differences | |

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|---|---|---|---|---|---|---|---|---|---|
| | Study 1 | College students: n=33<br>Experts: n=17<br>Novices: n=18 | *M*=22.7 *SD*=6.1<br>*M*=23.1 *SD*=3.3<br>Range: 15-35 | | Experts [*M*=13]<br>Novices [*M* =0] | Soccer-specific Perceptual Load task | Perceptual Load | *No sign*. expert-novice differences | 0.12 |
| | Study 2 | Experts n=15<br>Novices n=15 | *M*= 24 *SD*=3.2<br>*M*=21.8 *SD*=2.6<br>Range: 15-38 | | Experts [*M* =12.6]<br>Novices [*M* =0] | | | | 0.16 |
| Verburgh et al. (2014) | Study 1 | Total: n=126 (male)<br>High Division (HD) group: n=84<br>Low Division (LD) group: n=42 | *M*=11.9 *SD*=2.2<br>*M*=11.8, *SD*=2.3<br>Range: 8-12 | Soccer | HD= elite (Dutch youth academy)<br>[*M*= 6.7, *SD*=1.4]<br>LD= amateur (Dutch, average league level: 6, range from 4 to 9)<br>[*M*= 5.1, *SD*=1.5] | Stop Signal task (SSRT)<br>Attention Network Test<br>Visuospatial working memory task<br>[Full-scale IQ estimation]<br>[Physical activity estimation] | Motor Inhibition<br>Alerting & orienting attention, Executive network & attention<br>Working memory: Central executive & visuospatial sketchpad<br>[Wechsler Intelligence Scale for Children III]<br>[questionnaire: amount of physical activity] | HD *significantly* superior to LD<br>HD: *non-significant* slower mean reaction time on go trials than LD<br>HD: *significantly* larger MRT-gain in HD than LD<br>*No sign*. difference: orienting attention & executive attention<br>*No sign*. differences | 0.17 |
| Alves et al. (2013) | Study 1 | Total: n=154 (male & female)<br>Adult players: n=30<br>Male<br>Female<br>Junior players: n=57<br>Male<br>Female<br>Non-athlete | *M*=24.85 *SD*=4.40<br>*M*=20.55 *SD*=1.23<br>*M*=17.58 *SD*=0.92<br>*M*=16.27 *SD*=1.06<br>*M*=23.33 | Volleyball | Elite players: Brazilian Center for Development of Volleyball<br>Non-athletes: Brazilian universities & schools | Task switching Test<br>Stopping Task<br>Visual short-term memory Test<br>Useful field of view Test<br>Flanker test<br>Change detection | *Higher-level functions*: Cognitive shifting<br>Motor inhibition<br>*Memory*: Visual short-term memory, Visuo-spatial attentional processing<br>Breadth of visual attention<br>Selective attention | Athletes *sign*. faster than control on single task<br>Control *sign*. faster on go, athletes *sign*. faster on stop condition<br>Control: adult *sign*. faster than junior on stop; junior athletes *sign*. faster than junior control on stop; athletes *sign*. higher probability to stop than control | 0.27 |

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|---|---|---|---|---|---|---|---|---|---|
| | | adult control:<br>n=27<br>Male<br>Female<br>Non-athlete junior controls:<br>n=40<br>Male<br>Female | *SD*=3.04<br>*M*=21.55<br>*SD*=1.50<br>*M*=17.33<br>*SD*=1.13<br>*M*=16.45<br>*SD*=1.53 | | | | Visual attention & memory | No *sign*. difference in visual short-term memory, visuo-spatial attentional processing, breadth of visual attention, selective attention<br>Athletes *sign*. faster than controls in visual attention & memory | |
| Vestberg et al. (2012) | Study 1 | Total: n=57 (male & female)<br>High Division (HD) group: n=29<br>Lower Division (LD) group: n=28 | *M*=25,3<br>*SD*=4,2 | Soccer | HD= Swedish highest division soccer league<br>LD= Swedish 3rd national division (male) & Swedish 2nd national division (female) | Design Fluency (DF, D-KEFS)<br>-> main test<br>Colourword interference test (CWI)<br>Trail making test (TMT)<br>-> control tests | Metacognition (creativity, response inhibition, cognitive flexibility)<br>Cognitive flexibility<br>Scanning ability & short term memory | Cross-sectional tests:<br>Male & female players in both groups performed *sign*. above standard population average<br>HD players *significantly* better than LD players in metacognition, cognitive flexibility (only CWI4), scanning ability & short-term memory<br>Prospective test:<br>*Significant* correlation between DF & square root of points (goals & assists) | 0.36 |
| Furley & Memmert (2010) | Study 1 | Total: n=112 (male)<br>Athletes: n=54<br>Non-athletes: n=58 | *M*= 24.8<br>*SD*=2.7 | Basket ball | Sub-elite (college students)<br>[minimum: 10 years, not below 4th highest league in Germany] | Corsi Block-tapping task | Spatial working memory span | No *sign*. expertise difference | 0.07 |

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|---|---|---|---|---|---|---|---|---|---|
| Verburgh et al. (2016) | Study 1 | Total: n=168 (male)<br>Non athletes: n=51<br>Non-elite soccer players: n=48<br>Elite soccer players: n=69 | *M*= 10.4 *SD*=1.2<br>*M*=10.5 *SD*=1.3<br>*M* =10.6 *SD*=1.4<br>Range: 8-12 | Soccer | Non elite (regional amateur soccer clubs)<br>Elite (Dutch youth academy) | Stop Signal Task (SSRT)<br>Digit Span Forwards (of Digit Span task of WISC III)<br>Adapted version of Bergman-Nutley task (VTSM Forwards)<br>Modified version of Attention Network Test (ANT)<br>Modified version of Flanker task<br>[Wechsler intelligence scale for children III]<br>[BMI]<br>[Physical activity & sendentary behavior] | Motor Inhibition<br>*Memory*: Verbal short term memory<br>Visuospatial short term memory<br>*Attention*: Alerting & orienting attention, Executive function<br>Processing speed<br>[Full scale IQ] | Elite athletes *sign*. outperform both groups on inhibition, short term memory, working memory (only non-athletes)<br>Non elite athletes *sign*. better than non-athletes in short term and working memory | 0.21 |
| Zhang et al. (2009) | Study 1 | Total: n=37 (males & females)<br>Athletes: n=17<br>Non-athletes: n=20 | *M*=20.2 *SD*=1.9<br>*M*=19 *SD*=0.8<br>Range: 18-24 | Volley ball | National top level sports university [8-10 years]<br>Non-athletes | Multiple Object Tracking Task | Visuospatial attention | Elite: *sign*. shorter MRT than non-athlete | 0.6 |
| Vänttinen et al. (2010) | Study 1<br>Study 2 | Total: n=245 (male)<br>Sub-elite soccer players: n=123<br>Non-soccer playing children: n=122<br>10,12 & 14 year old groups: n=41 | Age groups 10,12,14 & 16<br>Age groups 10,12 & 14<br>Age groups 16 (2) & 19 (1) | Soccer | Sub-elite (regional team from Finland)<br>Sub-elite (regional team from Finland)<br>Addition of elite (U16: national team candidates, U19: national team) | Simple reaction time test (Wayne Saccadic Fixator board)<br>Peripheral awareness (Wayne Peripheral Awareness Trainer)<br>[Eye-hand-foot coordinatio | Processing speed<br>Breadth of visual attention<br>[Maturity status of players | Study 1 (cross-sectional):<br>Simple reaction time: Expertise difference only *sign*. in 16 year old group<br>Peripheral awareness: *Sign*. difference | 0.3 (study 3) |

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|---|---|---|---|---|---|---|---|---|---|
| | Study 3 | Age group 16: n=142 (sub-elite)<br>Age group 16: n=40 (elite)<br>Age group 19: n=16 (elite) | | | | n (Wayne Saccadic Fixator board)]<br>[Hormonal analysis (study 2)] | (testosterone)] | between 10-12, 14-16<br>Slightly but *not sign*. faster M(RT)<br>Study 3 (cross-sectional):<br>Simple reaction time:<br>Sub-elite & elite players *sign*. faster than non-soccer players<br>U16 elite *sign*. faster than U16 sub-elite<br>*No sign*. difference U16 elite & U19 elite, U16 elite & U16 sub-elite<br>Peripheral awareness:<br>*Sign*. difference between elite players & non-soccer players | |
| Williams et al. (2012) | Study 1 | Total: n=60 (male)<br>Elite: n=48<br>Non-elite: n=12 | *M*=17.8 *SD*= 1.4<br>*M*=19.8 *SD*=0.7 | Soccer | English youth academies<br>[*M*=10.4, $M_{\text{time}}$ in youth academy=7.2 *SD*=4.0]<br>Non-elite= amateur to semi-professional<br>[*M*=13.1] | Anticipation test (film-based paradigm)<br>Situational assessment (soccer action sequences different to first ones)<br>[Career Practice Questionnaire]<br>Soccer memory recall test | Ability to anticipate actions<br>Ability to assess situational information<br>[Participation history profiles]<br>Pattern recall ability | Perceptual-cognitive expertise (response accuracy):<br>Elite scored *sign*. higher than non-elite players | 0.82 |
| Brighina et al. (2011) | Study 1 | Total: n=56 (male)<br>Volleyball-players: n=24 | *M*=26.0 *SD*=4.3 | Volleyball, Rowing | Elite & semi-elite: Italian national level 12 & regional level 12 | Computerized version of modified Landmark task | Visuospatial attention Lateralization | RT:<br>Elite & sub-elite volleyball players *sign*. faster than | 0.3 |

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|---|---|---|---|---|---|---|---|---|---|
| | | National<br>Regional<br>Rowers: n=12<br>Sedentary controls: n=23 | *M*=25.6 *SD*=3.4<br>*M*=19.2 *SD*=4.0<br>*M*=24.8 *SD*=2.5 | | | | | rowers & controls<br>*No sign*. difference between elite & sub-elite volleyball players<br>Errors: Elite volleyball players: *sign*. lower number of errors compared to all other groups<br>Lateralization: Elite volleyball players: *sign*. fewer mistakes on the left compared to the right side than all others<br>*No sign*. difference in right side errors | |
| Furley & Memmert (2013) | Study 1 | Total: n=24 (male & female)<br>Experienced handball players: n=12<br>Non-experienced: n=12 | *M*=25.25 | Handball | Experts 1 [*M*=12.21]<br>Experts 2 [*M*=14.2] | Computer based sport task (Exp. 1: identify who has the ball) | Working memory | *No sign*. expertise difference | 0.08 |
| Memmert et al. (2009) | Study 1 | Total: n=120 (male & female)<br>Handball experts: n=40<br>Athletes non-team sport: n=40<br>Novice athletes: n=40 | *M*=24 Range: 22-29<br>*M*=25 Range: 22-27<br>*M*=23 Range: 21-29 | Handball, Track | Experts [more than 10] | Functional field of view<br>MOT task<br>Computer-based in-attentional blindness | *Attention tasks*<br>Ability to attend objects appearing far from fixation<br>Visuospatial attention<br>Ability to notice unexpected objects when performing attention-demanding | *No sign*. expertise / sports type difference | 0.12 |

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|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | monitoring task | | |
| Zoudji et al. (2010) | Study 1 | Total: 24 (male)<br>Elite group: n=12<br>Non-elite group: n=12 | *M*=22 *SD*=3.09<br>*M*=22 *SD*=2.13 | Soccer | Elite (top level team) [*M*=14.8 SD=3.7] | Decision making task (based on soccer-related situations)<br>Explicit memorization task | Decision making ability<br>Visuospatial short-term memory | Experts: *sign*. more correct responses (Response accuracy)<br>*No sign*. group or condition difference (Response consistency)<br>*No sign*. difference in response accuracy, response time | 0.25 |
| Reilly et al. (2000) | Study 1 | Total: n=31 (male)<br>Elite group: n=16<br>Sub-elite group: n=15 | *M*=16.4<br>*M*=16.4 Range: 16.2-16.6<br>*M*=16.4 Range: 15.8-16.7 | Soccer | Professional youth soccer<br>Local and school teams | Anticipation test<br>[Physiological Soccer-specific skills test] | Anticipation ability | Elite players: *sign*. better anticipatory performance (only on 1 vs 1 condition not on 3 vs 3, 11 vs 11) | 0.56 |
| Mallek et al. (2017) | Study 1 | Total: n=40 (male & female)<br>Super-Experts: n=13<br>Experts: n=14<br>Non-Experts: n=13 | *M*=22.17 *SD*=5.04<br>*M*=21.12 *SD*=1.3<br>*M*=23.89 *SD*=5.48 | Tennis | Elite<br>(Super-Experts = International level; Experts = good to very good in French federation's regional classification) | Visuo-motor tracking task (VMT) | Visuospatial attention | Initiation time: *Sign*. difference between experts, super-experts and non-experts<br>*No sign*. difference between experts & super-exp.<br>First interception time: *Sign*. short MRT for super-experts than both other groups<br>Movement time: *No sign*. difference<br>Time-to-peak-velocity: | 0.48 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | *Sign*. better performance in super-experts than both other groups<br>Peak velocity value: *No sign*. difference<br>Distance to target analysis: *Sign*. greater distance in non-experts than both expert groups | |
| Heppe et al. (2016) | Study 1 | Total: n=61 (male & female)<br>Elite: n=31<br>Recreational: n=30 | *M*=23.2 *SD*=4.1 Range: 16-34<br>*M*=21.7 *SD*=1.7 Range: 16-23 | Handball, Soccer, Volleyball | First or second division in Switzerland | Mental rotation experiment<br>d2 test | Mental rotation ability<br>Sustained attention | *Study 1*: *No sign*. difference between elite & recreational<br>*Study 2*: *No sign*. difference between elite & recreational | 0.1 |
| | Study 2 | Total: n=54 (male & female)<br>Elite: n=27<br>Recreational: n= 27 | *M*=24.6 *SD*=4.0 Range: 17-28<br>*M*=23.9 *SD*=3.2 Range: 20-31 | | First or second league in Germany | | | *Study 3*: Elite *sign*. better than recreational athletes on sustained attention | 0.28 |
| | Study 3 | Total: n=52<br>Elite: n=26<br>Recreational: n=26 | *M*=21.9 *SD*=3.81 Range: 17-32<br>*M*=22.0 *SD*=3.15 Range: 18-29 | | Soccer= 3rd national league team<br>Volleyball= first German division | | | | 0.33 |
| Kioumourtzoglou et al. (1998) | Study 1 | Total: n =28 (male)<br>Elite: n=13 | *M*=22.7 *SD*=1.2<br>*M*=21.7 *SD*=1.0 | Basketball | Greece national team | Vienna test system (memory task, advanced progressive | Memory & recognition | Elite *sign*. better in perceptual abilities (selective attention, prediction | 0.22 |

| | | | | | |
|---|---|---|---|---|---|
| | Controls:<br>n=15 | | matrices test)<br>SuperLab (sport-specfic video)<br>[Laboratory measurements] | Processing speed & motor inhibition<br>[Motor abilities] | assessment) & cognitive abilities<br>*No sign*. difference for speed of perception or response selection patterns or memory patterns of information |

## Appendix II: Publication II

### The Relationship Between Cognitive Functions and Sport-Specific Motor Skills in Elite Youth Soccer Players.

**Reference:**

Scharfen, H. E., & Memmert, D. (2019). The Relationship Between Cognitive Functions and Sport-Specific Motor Skills in Elite Youth Soccer Players. *Frontiers in Psychology*, *10*, 817.

# ABSTRACT

The aim of the present study was to examine the relationship between basic cognitive functions and sport-specific motor skills in elite youth soccer players. A total of 15 elite youth soccer players aged 11–13 years performed a computer-based test battery measuring the attention window (AW), perceptual load (PL), working memory capacity (WMC), and multiple object tracking (MOT). Another set of tests was used to asses speed abilities and football-specific technical skills (sprint, change of direction, dribbling, ball control, shooting, and juggling). Spearman's correlation tests showed that the diagonal AW was positively associated with dribbling skills (rs = 0.656) which indicates that a broader AW could be beneficial for highly demanding motor skills like dribbling. WMC was positively related to dribbling (rs = 0.562), ball control (rs = 0.669), and ball juggling (rs = 0.727). Additionally, the cumulated score of all cognitive tests was positively related to the cumulated motor test score (rs = 0.614) which supports the interplay of physical and psychological skills. Our findings highlight the need for more, and especially longitudinal, studies to enhance the knowledge of cognition-motor skill relationships for talent identification, talent development, and performance in soccer.

*Keywords:* elite, youth, cognitive functions, soccer, motor skills, sport-specific skills

# INTRODUCTION

High-demand sports require extraordinary physiological capacities combined with outstanding abilities in the areas of motor control, perception, and cognitive functioning. Two recent meta- analysis (Voss et al., 2010; Scharfen and Memmert, 2019) showed small to middle effects of basic cognitive functions in experts and elite-athletes which may point at their superiority in terms of basal cognitive functions. Besides the physiological abilities, previous research mostly focused on the cognitive skills of elite adult athletes (Mann et al., 2007; Voss et al., 2010; Scharfen and Memmert, 2019). In terms of elite youth athletes, especially soccer players, current research mainly studied – on the one hand – the physical or physiological prerequisites of elite youth soccer players (Unnithan et al., 2012; Waldron and Murphy, 2013; Abade et al., 2014; Murr et al., 2018) or – on the other hand – the psychological prerequisites, that is the cognitive functions of elite youth soccer players (Verburgh et al., 2014, 2016; Balakova et al., 2015; Huijgen et al., 2015; Vestberg et al., 2017) in isolation. To the best of our knowledge, the combination of both motor (i.e., soccer- specific motor skills) and basic psychological (i.e., cognitive functions) has not yet been examined. Therefore, the present study is unique as it connects basic psychological (cognitive functions) with motor (soccer-specific motor skills) aspects of elite youth soccer players. Cognitive skills refer to the ability to identify and acquire environmental information in order to integrate them with existing knowledge (Marteniuk, 1976). This allows the individual to select and execute the appropriate responses. An especially interesting and important subgroup of these skills are executive functions (EF) which describe cognitive processes that regulate thoughts and actions, especially in non-routine situations (Friedman et al., 2014). The EF are further subdivided into core EF (CEF), which can be defined as working memory, cognitive flexibility and inhibitory control, and higher-level EF (HEF), involving reasoning, problem solving, and planning (Diamond, 2013). These EF skills mature at different ages, as they depend on different prefrontal structures. The neuronal structure underlying HEF is the prefrontal cortex which matures slowly and last in development; full capacity is reached between 20 and 29 years of age (De Luca et al., 2003; Luciana et al., 2005). In contrast CEF develop its total capacity earlier in the lifespan, most often before early adolescence (Crone et al., 2006). We related their motor skills to CEFs [working memory, object tracking, inhibition under perceptual load (PL), and flexibility to widen the attention window (AW)] as these develop earlier than HEFs and may be a key predictor for cognitive functions this early in maturation.

Additionally, distinct motor-cognition interactions were proposed with strong mutual influences in terms of (i) functional brain networks (e.g., Leisman et al., 2016; Ptak et al., 2017), (ii) structural brain networks (e.g., Hanakawa, 2011; Koziol et al., 2012; Bigelow and Agrawal, 2015; Gao et al., 2018). More specifically, recent studies show that (1) cognition emerges from motor function in young children (i.e., 1.5–6 years of age) – they predicted several cognitive functions like mental rotation ability (Jansen and Heil, 2010; Lehmann et al., 2014), working memory (Lehmann et al., 2014; Gottwald et al., 2016), inhibition (Gottwald et al., 2016) and (2) that exercise improves cognitive function (Hillman et al., 2009; for review see Tomporowski et al., 2015). Additionally, a review by van der Fels et al. (2015) found weak-to-strong relations between motor and cognitive skills, especially in pre- pubertal children (i.e., under 13 years of age) whereas Hartman et al. (2010) reported correlations between motor performance and EF in children with intellectual disabilities. Grooms and Onate (2016) state that the ability to maintain motor control in the unpredictable sport environment demands a complex central nervous system integration ofconstantly changing inputs, the processing of which also depends on cognitive functions. However, this study is related to the cognitive skills approach as basic cognitive functions are analyzed. Having the value for talent scouting in mind, the current research sets a focus on youth elite athletes. However, to the best of our knowledge none of these interactions have been examined on a behavioral level in an elite-sports context yet with children in this development stage (i.e., around 12 years of age). In addition, we are following the call of Leisman et al. (2016) by conducting this examination.

### Review of Literature on Cognitive Functions and Skills in Elite Youth Soccer Players

In the following, several studies regarding cognitive functions within similar study designs are described (i.e., cross-sectional, elite-athletes, elite-athletes, youth, and age range from 9 to 14 years). Verburgh et al. (2014), conducted a study with the aim to examine a broad range of cognitive skills in elite and sub-elite soccer players (n = 126), with an average age of 11.8 years. They measured cognitive abilities, motor inhibition, alerting and orienting, executive network and executive attention, as well as visuospatial working memory. They used a stop signal task, a modified flanker attention network test, and an adapted Bergman-Nutley task (VTSM forward and backward). They reported heterogeneous results: The elite group outperformed the sub-elite in terms of reaction time in the motor inhibition task as well as in the alerting attention task. No differences were found in orienting attention, executive attention, or working memory capacity (WMC). In another study, the same research group (Verburgh et al.,2016), carried out a similar investigation of elite and sub-elite soccer players and non-athletes (n = 168, M = 10.5 years of age); they checked for motor inhibition, verbal short-term memory, working memory, and visuospatial short-term memory. The elite players significantly outperformed the sub-elite players and the non-athletes in terms of inhibition, short-term memory, and partially working memory. Furthermore, the sub-elite players outperformed the non-athletes in terms of short-term memory and working memory. Moreover, Vestberg et al. (2017), investigated 30 elite soccer players (M = 14.9) in regard to their cognitive functions. Significant results were found for processing speed, simple attention, and WMC in which the elite players performed highly above the level of the normal population. Additionally, working memory and multiprocessing as well as the combination of both functions positively correlated with scored goals whereas no significant correlation was found between processing speed or attention and scored goals. In contrast to these findings by Vestberg and colleagues which support superior cognitive functions in youth elite athletes, some other studies did not show this exceptionality. For example, Balakova et al. (2015), studied a wide range of cognitive abilities such as visuospatial short-term working memory, reaction ability, and attention by usage of the Vienna test system in 91 elite soccer players (Mage = 13). No differences were found between talented and less talented players except for the ability of spatial and temporal movement anticipation. Also, Granacher and Borde (2017), reported no significant expertise differences when testing elite youth athletes (Mage = 9.5) and non-athletes regarding concentration and attention. For an overview see Table 1.

Table 1. *Cognitive measurements of elite youth athletes*

| Author | Age | Academy / Country | Type of sport | Test | Measured Cognitive Abilities | Results |
|---|---|---|---|---|---|---|
| Granacher et al. (2017) | 9,5 | Elite-school of sport Germany | Various sports (including soccer) | d2 test | concentration & attention | *No sign*. Elite differences |
| Verburgh et al. (2016) | 10,6 | Professional youth soccer academy Netherlands | Soccer | Stop signal task<br>Digit Span Forwards<br>adapted version of Bergman-Nutley task | motor inhibition<br>verbal short-term memory (STM) & working memory (WM)<br>visuospatial short-term memory | Elite *sign*. better than sub-elite & non-athletes: inhibition, STM, WM (not better than sub-elite)<br>Sub-elite athletes *sign*. outperform non-athletes in STM, WM<br>Time spent in organized sports *sign*. positively correlated with inhibition, |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | (VTSM Forwards) | | STM, WM, lapses of attention |
| Verburgh et al. (2014) | 11,8 | Professional youth soccer academy Netherlands | Soccer | Stop signal task<br>modified Attention Network test<br>modified Flanker task<br>adapted version of Bergman-Nutley task (VTSM Forwards & Backwards) | motor inhibition<br>alerting & orienting<br>executive network & attention<br>working memory (visuospatial sketchpad & central executive) | Elite *sign*. better than sub-elite (SSRT) but slower RT on go trials<br>Elite with *sign*. larger gain in RT, no differences in orienting attention<br>*No sign*. Elite differences in executive network & attention, working memory |
| Balakova et al. (2015) | 13 | Professional youth soccer academy Czech Republic | Soccer | Vienna Test System:<br>reaction test<br>Corsi Block-Tapping test<br>long-term selective attention test<br>visual-pursuit test<br>Stroop test<br>visual memory test<br>time/movement anticipation test<br>determination test<br>gestalt perception test | cognitive abilities<br>ability to react<br>visuospatial short-term working memory<br>focused attention<br>visual perception<br>color-word interference<br>short-term memory<br>spatial/temporal movement anticipation<br>stress tolerance, reactive<br>special ability test | *No sign*. Elite differences except the anticipation test (talented within group *sign*. outperformed less talented group) |
| Vaeyens et al. (2007) | 14,7 | Professional youth soccer academy Belgium | Soccer | Soccer specific video clips (gaze behavior) | decision making process | Successful within elite group *sign*. quicker in all conditions than less successful group & more accurate in decision making (except condition 2 vs 1) |
| Vestberg et al. (2017) | 14,9 | Professional youth soccer academy Sweden | Soccer | CogStateSports | demanding working memory (dWM): | Elite players *sign*. above level of normal population: |

| | | | |
|---|---|---|---|
| | | attention, processing speed, learning, working memory | processing speed, attention & dWM<br>No *sign*. Correlation between processing speed / attention & scored goals<br>*Sign*. positive Correlation between dWM, DF, composite score of DF & dWM & scored goals |
| | Design Fluency (DF) | multiprocessing (creativity, response inhibition, cognitive flexibility) | |
| | Colorword interference test (Stroop test) | cognitive flexibility, verbal inhibition | |
| | Trail making test | scanning ability, multiprocessing, cognitive flexibility, short-term memory | |

### The Present Research

Reviewing the literature on cognitive skills in elite athletes in general, it is conspicuous that there are much fewer studies on youth elite players – especially in the age range from 9 to 14 – (n = 6) (see Table 1) than there are on adult elite players – 18 years of age or older – (n = 23). This unpublished review was conducted by the authors in February 2018 by using following inclusion criteria: cross-sectional study, elite- or expert-athletes, examination of active athletes, statement of a specific type of sport. Additionally, the reviewed literature on cognitive skills in youth elite athletes reveals conflicting results and heterogeneity in terms of the used tests (a comparison of employed cognitive tests is illustrated in the supplemental material). The present study aims to enrich the literature on cognitive functions in youth elite soccer players by studying the interplay between these functions and motor/technical skills for the first time. Therefore, the purpose of our research is to set a starting point and open new pathways for research and discussion in terms of the link between cognition and motor skills in youth elite athletes. Furthermore, this linkage has been depicted only on brain-structural and functional dimensions. Therefore, it should be analyzed on a behavioral level. More specifically, the aim ofthis study was to investigate the relation between cognitive functions [working memory, PL, multiple object tracking (MOT), and AW] and soccer specific motor skills (sprint, change of direction, dribbling, ball control, and ball juggling) in soccer players aged between 11 and 13. These cognitive tests are used based on previous research depicting their crucial importance in elite soccer: (1) working memory; (2) PL (e.g., Vestberg et al., 2012; Verburgh et al., 2014, 2016; Huijgen et al., 2015); (3) MOT (e.g., Faubert, 2013; Romeas et al., 2016); and (4) AW (Hüttermann et al., 2014). As this is a first of its kind investigation the sample size is quite small, because this first step in a possible opening of new research pathways should analyze whether it is worthwhile in the first place. If so, future studies would need to examine this in larger populations.

## Materials and Methods

### Participants

A total of 19 elite youth soccer players from the talent development program of the youth academy of a professional German soccer club were recruited. The participants were boys born between 2005 and 2006 (Mage = 12.72, *SD* age = 0.45) and had started playing soccer at approximately 5.2 years of age (SD = 1.4). At the time of data collection, their teams were playing at the top level of their respective age group and the players were part of a professional youth academy for an average of 2.75 years (SD = 1.47). Participants were not diagnosed with any behavioral, learning, or medical conditions that might influence cognitive abilities. Four datasets of players had to be excluded, two due to missing motor datasets and two because of their positions as goalkeepers, which highly influenced the motor test in a negative way. Therefore, 15 datasets were used for the study. Written informed consent was obtained from every participant before commencing the experiment. The study was carried out in accordance with the Helsinki Declaration of 1975 and was approved by the ethics committee of the German Sport University Cologne.

### Procedure and Materials

Data of the cognitive tests were collected in a separate and quiet room. The cognitive test session was conducted prior to a soccer training and consisted of one session lasting approximately one hour with two players performing the tests simultaneously. We used a battery of four tasks to explore individual differences in basic cognitive mechanisms. Each task is described below. The order of the cognitive tests and the different conditions within were randomized. Participants were instructed to sit in a comfortable position leaning against the backrest of the chair, so that the distance to the screen (approximately 45 cm) was the same for all the players. One experimenter tested all players in a standardized process and was blind to the hypotheses. Additionally, the motor performance test was acquired in a gym approximately 4 months prior to the cognitive tests. This difference regarding the time point of measurement exists due to the fact that the motor test was not conducted for the purpose of this study solely as this test battery is part of the German Soccer Association (DFB) talent-development program and is conducted twice a year in every professional youth academy and at the DFB bases of the talent-development program. Therefore, all players did know this test battery already. Test leaders were either licensed soccer coaches of the youth academy or the DFB talent-development program. The data of this motor performance test were used, because they were analyzed and confirmed for objectivity, reliability and validity in large scale study (*N* = 68,158) by Höner et al. (2015).

**Cognitive tests.** For stimulus presentation, E-Prime 1.2 (Psychology Software Tools Inc.) and two 15-inch computer screens with a resolution of 1,024 x 786 pixels were used.

The *Attention Window Task* (AWT) by Hüttermann et al. (2013), was used to assess the individual attention breadth on diagonal axis. During each trial, participants were instructed to fixate a central point [21] and try to spot a white triangle within a circle (1.1° diameter) among square distractors (1.1° x 1.1°). Across trials, the target appeared at varying distances from the fixation point (10°, 20°, 30°) along one of eight equally spaced radial lines that originated from a square in the center of the display (45° apart). This random display was flashed for 12 ms and was followed by a colorful mask (100 ms). After every mask, subjects were asked to indicate how many white triangles they had just seen in the different locations depending on the orientation of the items. Participants completed 180 trials. This particular task measures how well people can attend to objects appearing far from fixation. The dependent measure was the score of the diagonal AW and dividing the total value by the number of the dimensions (i.e. three).

The well-established *Working Memory Span Test* (WM) by Conway et al. (2005), measures the athlete's ability to direct attention towards the current task without getting distracted by other thoughts. More specifically, we used a counting span task (see Kane et al., 2004 for a detailed description), as the simplicity of this processing task makes it usable for almost any type of participants (Conway et al., 2005). The instructions were presented as a written text on the computer screen. The counting span task involved counting specific shapes among distractors and then remembering the count totals for later recall. Each stimulus display contained randomly arranged dark blue circles, green circles, and dark blue squares. The task of the participants was to count aloud the dark blue circles and then name the total count aloud at the end. A recall mask occurred after two to six stimulus displays into which participants had to fill their memorized count totals in the exact order they had been displayed in. The participants counting span score was a partial credit load score (cf. Conway et al., 2005) which represents the sum of all correctly recalled elements - whereby a correctly recalled item from a set containing two items receives 2 points, and a correctly recalled item from a set with 6 items receives 6 points - divided by the maximum possible score. The test consisted of 15 trials. The dependent measure was the score of correctly memorized objects in percentage.

The *Perceptual Load Test* (PL) by Beck and Lavie (2005), is a measure of inhibition ability as it determines to what extent participants are distracted by stimuli which are totally irrelevant for their task. Participants performed the soccer-specific PL task (Furley et al., 2013) starting with two example blocks (one high and one low load), followed by eight experimental blocks alternating between blocks with low and high load. All participants started out with the high-load block. A fixation point of 1,000 ms was displayed before each trial located in the center of the screen immediately followed by the task display with the soccer-specific arrangement and distractor. The task displays were presented for 100 ms. Subjects were told to ignore the distractor letter and to indicate as quickly and as accurately as possible to which of the target items (the player) the dot (the ball) was allocated. The distractor always showed up on a fixation point (Beck & Lavie, 2005). Participants responded to the target stimuli either by pressing ‘’n’’ or ‘’c’’ on the keyboard. The subjects were instructed to press ‘’n’’ for an X target and ‘’c’’ for an O target. A new trial was triggered by the participant’s response or response omissions within 2 s. After each trial, feedback about incorrect responses or omissions was given by means of a computer sound. After each block, participants were reminded of the key assignments. The test consisted of 160 trials. The dependent measure was the reaction time of perceptual load related to the condition of low and high distraction.

The *Motion Object Tracking Test* (MOT) by Alvarez & Franconeri (2007) measures up to which speed threshold participants are able to track several relevant moving objects. Participants monitored the positions of a set of moving circles on a computer monitor. The display initially contained four green circles and three blue ones (1.1° diameter). After 3 seconds of resting state, the blue items turned green and were identical to the targets and all circles began moving while participants tried to keep track of the positions of the initially green items. The test is adaptive so speed thresholds and number of trials depend on the players' abilities. After eight seconds the circles stopped moving and the participants had to select and mark the initially three blue circles. The dependent measure was the number of correctly tracked and marked circles. This task should reveal individual differences in the ability to divide and maintain attention on multiple independently moving objects.

**Motor performance test.** This diverse test battery consists of six tests (sprint 20-meter, acceleration 10-meter, change of direction, dribbling, ball control, ball juggling) which assess the motor skills of soccer athletes (Höner et al., 2015).

The *Sprint test* is used to track the time an athlete needs to run 10 and 20 meters as fast as possible. The test structure consists of three light barrier pairs, one pair at the start, one at the 10 meter point and one at the 20 meter point. The task of the athlete is to run as fast as possible through all light barriers. The dependent measure was time (in seconds) at 10 and 20 meters.

The *Change of Direction test* is used to assess how fast the athlete is able to change directions in a preset running parkour – a fixed positioning of bars to direct the athlete in a certain change of direction. The parkour consists of a 3 meter sprint to the first slalom parkour – made of three bars – then again a 3 meter sprint to the second slalom parkour and then the last 3 meter sprint to the finish. The time needed for this task is measured by light barriers at the starting and end point of the parkour. The dependent measure was the total time needed to absolve the parkour.

The *Dribbling test* measures the ability to dribble as fast and as accurate as possible with a ball through a preset parkour with different direction changes. The parkour and the dependent measure used for this task is the same as in the *Change of Direction test*.

The *Ball Control test* measures the ability to control and pass the ball in a small square as fast and as accurate as possible. The athlete is standing in the middle of the square (1,5 x 1,5 meter) which consists of a bounce-wall on the left and on the right at a distance of 3 meter. The task is to pass six passes alternately to the two bounce-walls as fast as possible. The passes have to be executed while standing in the middle zone and by using at least two contacts for each pass. The test is over when the last pass is received in the middle zone. The dependent measure was the total time needed to absolve the six passes.

The *Ball Juggling test* measures the ability to juggle the ball in a preset parkour. The parkour consists of two adjacent circles (3 x 3 meter) shaped like an eight. The player starts standing in the middle of the two circles with the ball in his hand. His task is to juggle as fast as possible through the parkour. He gets a point each time he tackles the parkour without a mistake. A mistake was defined as a situation in which the ball touches the ground. The test lasts about 45 seconds. The dependent measure was the total number of points for successfully absolving the parkour.

We calculated one cumulated value for all cognitive tests (*Cognition Total*) and one for the motor performance tests (*Motor Total)* by adding up the scores of the dependent measures of each motor performance test and dividing the sum by the number of dependent measure variables. All values were z-standardized prior to this calculation. As reaction times for low and for high load in the perceptual load test constitute different cognitive measures (Beck & Lavie, 2005; Furley et al., 2013), we included both values in the Cognition Total Score. *Motor Total* included the overall score of the motor test battery as well which was stated by the test leaders of the motor performance tests to gather a general impression of the performance. This is important to know, as that overall score of the motor test battery differs from the total score calculated by the authors as the first score does not include the test of acceleration.

## Statistical Analyses

Data was analyzed using IBM SPSS Statistics 23.0.0. Shapiro-Wilk test was used for testing for normal distributions. Not all variables were normally distributed, as assessed by Shapiro-Wilk's test ($p < .05$). Therefore, the Spearman's correlation coefficient test was used to investigate the correlation between the player's cognitive and motor test results. Moreover, effect sizes (cohen's $d$) were calculated for every correlation coefficient by transforming the $r$

into a *d* value according to the formula of Ellis (2010) and values of .10, .30 and .50 represent small, medium and large effect size estimates (Cohen, 1988).

## Results

Descriptive statistics of each test are illustrated in Table 2.

Table 2. *Descriptive statistics of each cognitive and motor test and their dependent measures*

| | Mean Value | Standard Deviation |
|---|---|---|
| AW diagonal | 4.01 | 3.46 |
| MOT | 988.73 | 232.85 |
| PL high rt | -4.93 | 44.42 |
| PL low rt | 17.71 | 54.98 |
| WMC | .56 | .14 |
| Speed (20m) | 3.43 | .17 |
| Acceleration (10 m) | 1.98 | .10 |
| COD | 7.95 | .38 |
| Dribbling | 1.44 | .95 |
| Ball control | 9.40 | 1.11 |
| Ball juggling | 4.77 | 3.77 |
| Total Score | 103.97 | 1.91 |

*Note.* For all measurements, the number of participants was equal (*n* = 15), AW = Attention Window in cm, MOT= Multiple Object Tracking in number of correctly tracked targets, PL = Perceptual Load, RT = Reaction Time in seconds, WM = Working Memory in %, COD= Change of Direction

Firstly, there was a significant correlation between the cumulated score *Cognition Total* and *Motor Total*, $r_s$ (13) = .614, $p$ = .015. Therefore, superior performance in the cognition tests significantly correlates positively with superior performance in the motor tests. Due to this result we further checked for correlations that cause this finding.

In terms of diagonal Attention Window (AW) there were no statistically significant correlations between the motor tests except for the dribbling test ($r_s$ (13) = .656, $p$ = .008) as depicted in Table 3. The MOT task was not significantly associated with any of the other tests. Furthermore, there were no significant correlations between the PL reaction times and all other tests. However, there were significant correlations between the WMC test and the test of Dribbling ($r_s$ (13) = .562, $p$ = .029), Ball control ($r_s$ (13) = .669, $p$ = .006), Ball juggling ($r_s$ (13) = .727, $p$ = .002), and the Total Score ($r_s$ (13) = .553, $p$ = .033). Thus, superior performance in the working memory capacity test significantly correlates positively with superior performance in the motor tests.

Table 3. *Correlations $r_s$ between cognitive and motor tests*

| | Speed (20 m) | Acceleration (10 m) | COD | Dribbling | Ball control | Ball-Juggling | Total Score |
|---|---|---|---|---|---|---|---|
| MAW diagonal | | | | | | | |
| Correlation coefficient | .087 | -.014 | .339 | .656** | .380 | .098 | .395 |
| Sig. (2- fold) | .758 | .961 | .216 | .008 | .162 | .729 | .145 |
| Effect size (d) | .175 | -.027 | .721 | 1.74 | .822 | .197 | .860 |
| MOT | | | | | | | |
| Correlation coefficient | -.047 | -.126 | -.032 | .125 | .146 | .123 | .175 |
| Sig. (2- fold) | .869 | .656 | .909 | .657 | .603 | .664 | .533 |
| Effect size (d) | -.093 | -.254 | -.064 | -252 | -294 | -248 | .356 |
| PL high reaction time | | | | | | | |
| Correlation coefficient | -.029 | -.143 | .211 | .318 | .425 | .418 | .396 |
| Sig. (2- fold) | .919 | .610 | .449 | .248 | .114 | .121 | .143 |
| Effect size (d) | -.058 | -.289 | .432 | .671 | .939 | .921 | .863 |
| PL low reaction time | | | | | | | |
| Correlation coefficient | -.095 | -.056 | -.409 | -.396 | .075 | .168 | .021 |
| Sig. (2- fold) | .737 | .844 | .130 | .143 | .791 | .551 | .940 |
| Effect size (d) | -.191 | -.112 | -.895 | -.863 | .150 | .341 | .430 |
| WMC | | | | | | | |
| Correlation coefficient | -.260 | -.249 | .197 | .562* | .669** | .727** | .553* |
| Sig. (2-fold) | .350 | .371 | .480 | .029 | .006 | .002 | .033 |
| Effect size (d) | -.539 | -.513 | .402 | 1.39 | 1.81 | 2.12 | 1.33 |

| | Motor Total |
|---|---|
| Cognition Total<br>Correlation coefficient | .614* |
| Sig. (2-fold) | .015 |
| Effect size (d) | 1.56 |

** The correlation is significant at .01 level (twofold)

* The correlation is significant at .05 level (twofold)

*Note.* For all measurements, the number of participants was equal (*n* = 15). COD=change of direction, AW= attention window, MOT= multiple object tracking, PL= perceptual load, WMC= working memory capacity

## DISCUSSION

The current study addressed the relationship between cognitive functioning and specific motor abilities in elite youth soccer players. The aim was to expand the knowledge of the relationship between basic cognitive skills and soccer specific motor skills. Results showed that the diagonal AW was positively correlated with dribbling performance. This may suggest that athletes who have a wider attention window also have advanced dribbling skills. Moreover, these findings could imply that a broad AW enhances the players' skills regarding highly demanding motor tasks, because they may be able to perceive many optical stimuli in their visual attention window. This may enable them to execute early reactions in their sensorimotor system to make their performance more efficient. For example, in a game situation where the athlete is dribbling and simultaneously has to keep an eye on the ball, his teammates and his opponents. In this case a broad AW could be beneficial for example to avoid contact with opponents and dribbling in spaces already covered by teammates. These results are in line with previous meta-analysis (Voss et al., 2010; Scharfen & Memmert, 2019) which implicated superior cognitive abilities in elite athletes. Another positive relationship was reported for WMC and dribbling as well as for ball control, ball juggling, and total score. Especially these findings regarding WMC are in line with studies examining cognitive functions in elite athletes mentioned earlier. Previous research for example indicated a) that a higher WM capacity is associated with a superior athletic performance as well as b) that time spent in organized sports positively correlates with WM (e.g. Verburgh et al., 2014, 2016). Nevertheless, there are also other studies which did not indicate this relationship (e.g., Balakova et al., 2015; Furley & Memmert, 2010). Additionally, the missing correlation of the motor tests with the MOT and the PL test could be due to the fact that the motor tasks do not include similar demands. For example, in the motor performance tests used here there is no task in which multiple objects or players need to be tracked simultaneously. Therefore, there is no situation that requires similar skills or has the same task structure like the MOT. Although several studies related to the perception-action coupling approach (Renshaw & Davids, 2004; Davids et al., 2013; Pinder et al., 2009) already proved the link of specific perceptual abilities and performance, this is the first study to our knowledge that shows a positive correlation between the cumulated scores of all basic cognitive and all motor tests which could point at a strong interplay of physical and psychological skills. These results are in line with mutually influencing cognition- and motor-networks on a basic functional (Leisman et al., 2016; Ptak et al., 2017) and structural level (Koziol et al., 2012; Bigelow & Agrawal, 2015; Gao et al., 2018). Furthermore, they could also be a hint for the use of similar neural networks (Hanakawa, 2011) and of the same brain regions (Leisman et al., 2016) when carrying out different cognitive tasks and motor skills. Additionally, these findings are in agreement with Grooms & Onate (2016) who state the ability to maintain motor control in the unpredictable sport environment demands complex central nervous system integration of a constantly changing profile of sensory inputs. Moreover, it is also in consonance with their statement that the incorporation of cognitive elements ranging from dual tasks, responding to stimuli, anticipation, decision making and programming motion relative to external targets may degrade neuromuscular control relative to movement without such factors. In terms of developmental motor-cognition interactions these findings point at the same direction as previous research did with 1) younger children (Jansen & Heil, 2010; Gottwald et al., 2016; Lehman et al., 2018), 2) cognitive improvements as a function of physical exercise (Hilmann et al., 2009; Tomporowski et al., 2015) and 3) strong motor-cognition relations in pre-pubertal children (i.e. under 13 years of age) (for review see van der Fels et al., 2014).

Although the results are based on a cross-sectional study and await replication in a design that allows causal interpretations, the data unveils a possible explanation for differences in performance among elite youth soccer players in terms of their cognitive function and their specific motor skills. WMC and AW may prove relevant for talent identification purposes as they are strongly associated with ball juggling, ball dribbling, and especially the total motor skill score and pace, which all are of major interest in professional soccer clubs. By adding these cognitive tests to the physical ones (those who correlated significantly, i.e. dribbling, ball control, ball juggling and the total score) the impressions and values derived from the physical tests could be strengthened and besides the information about the player’s profile in terms of cognitive function would be extended. In terms of talent development, playing soccer at a high level of performance each day, that is in a talent selection team of a professional soccer club, seems to be associated with the level and development of most of the cognitive skills. This could possibly indicate that these cognitive skills may crucial for talent development and could be simultaneously promoted via these talent programs of professional soccer clubs – a positive reciprocal development so to speak. Nevertheless, as we cannot draw causal conclusions based on our data, talent development might be influenced by a third variable. However, to the best of our knowledge, this study is the first that examines the combination of several cognitive functions and soccer-specific motor skills in young soccer experts. Future studies are clearly needed to investigate this promising relationship further.

We should also acknowledge limitations of the present study. The used motor test analyzes basic soccer-specific motor skills like dribbling and juggling which are able to distinguish elite from recreational soccer players but not elite from sub-elite (Meylan et al., 2010). The study, thus, does not cover the whole spectrum of the complex soccer game. One example is that no HEFs were assessed which are crucial for the complex game as well (Vestberg et al., 2017). Therefore, some core tactical abilities, such as multiple object tracking in a dynamic surrounding like small-sided games are missing. Furthermore, although the change of direction test is well validated, it is a limitation, as it lacks external stimuli on which the changes of direction depend in a real game situation. The differentiation between change of direction and agility is crucial in this regard (Haff & Tripplet, 2016). There is no situation in the game, in which a player has to change his direction in a preset order. Additionally, a high number of correlations in our study were not significant. Thus, more replication research in this field is clearly needed (Klein et al., 2012). Furthermore, the study lacks highly statistical power as the unique sample is relatively small due to the fact that elite youth soccer players have been examined whose accessibility is strictly limited for most of the time.

Consequently, there are several recommendations for future research derived from limitations of this study. First, linking cognitive test results (especially HEF) to 1) tests that are able to measure more complex and diverse soccer- and sport-specific skills, which is necessary to expand the knowledge about these correlations (e.g. small-sided games and agility test with external stimuli) and 2) objective performance measurements (e.g. assessment of performance during game play) to strengthen possible relationships and replicate findings from previous studies (Vestberg et al., 2017; Vestberg et al., 2012). However, it should be noted that performance objectives like scored goals are difficult to measure in young athletes due to highly varying positions of players and due to the fact that the likelihood of scoring goals is highly varying depending on the position. Regarding 1) it will be a challenge to include those tests as there may occur problems in terms of objectivity and reliability. Secondly, longitudinal measurements with a larger number of players are necessary to examine the age-related interaction of cognitive functions, soccer-specific motor skills, and their development. Especially considering the individual timing of maturation of cognitive functions (Best et al., 2009). Moreover, using longitudinal study designs would enable researchers to search for additional influential factors as well as to conclude and uncover for further causal relationships as this possibility is very limited in cross-sectional studies. Finally, investigations of HEFs are needed as well as they are an important aspect of the complex game as well (Vestberg et al., 2017).

To summarize, we found that the cognitive functions attention window and working memory are partly associated with some specific and core motor skills whereas the sum of all cognitive and all motor skills are strongly correlated as well. Additionally, the cognitive tests multiple object tracking and perceptual load test did not show any relation to the tested motor skills.

Although one has to keep in mind that this only a first attempt to understand the relationship between cognitive and motor behavior one may have a look at the direction at which these results could point. Namely, these findings could be important from both a theoretical and a practical perspective. From a theoretical point of view, this may highlight the importance of cognitive training models that are based on neuro-cognitive knowledge as well as the need for more sophisticated models and theories that explain the relationship of movements i.e. technique and cognition. The usage of such training models increases the cognitive functions and possibly the motor technique skills, which is in line with recommendations of van der Fels et al. (2014) and with the results above showing correlations of both abilities. The arising need for these cognitive training models is in line with the increasing evidence that some of these cognitive functions like attention window and multiple object tracking (Romeas et al., 2016) as well as working memory (Klingberg, 2010) are trainable. Nevertheless, the transfer to the real game is not clearly established for every improvement yet. Furthermore, research suggests that a combination of cognitive and physical training is more beneficial for the athletes in terms of cognitive functions, mental health and neurogenesis than only one of them conducted separately (Curlik & Shor, 2012).

From a practical point of view, knowledge about the relationship between cognition and motor skills, in other words between the brain-muscle interplay, could possibly help sport clubs to be able to scout for talents and new players in a more effective and holistic way. This sophisticated scouting system could be created by adding a cognitive scouting or test tool to the categories of technique, athletics, and tactics. Adding this cognitive tool is backed up by studies that report a high linkage and overlap between cognitive functions and game intelligence, which is crucial for success in elite sports and still hardly measurable (e.g., Vestberg et al., 2017, 2012). Additionally, this knowledge may be used by coaches to enhance their player’s cognitive abilities and eventually some of their motor skills as well as improving working memory for general motor skills. Referring to this, individual soccer training programs could be created based on these relationships to enhance soccer performance on the pitch.

Furthermore, as these results may point in the same direction as the perception-action coupling approach, it could perhaps help coaches to create training programs and exercises which do not isolate sport specific perception (i.e. cognitive functions) and action (i.e. motor skills) but rather enhance both in unison as these couplings are required and highly challenged in real game situations. Moreover, training those couplings and incorporating cognitive elements may not only enhance performance (Appelbaum & Erikson, 2018; Belling & Ward, 2015; Grooms et al., 2015; Hadlow et al., 2018; Broadbent et al., 2015) but also prevent athletes from injuries (Grooms et al., 2015; Grooms & Onate, 2016).

Further research should provide more evidence for elite youth athletes as specifically these early years in a player’s career are crucial for the development of the athlete’s cognitive abilities. The sensitive learning phases occur during this period of time which highlights the importance of this age group for further development of the athlete’s skills.

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Conflict

## Appendix III: Publication III

# The relationship of executive functions and physical abilities in elite soccer players

**Reference:**

Scharfen, H. E., & Memmert, D. (2021). The relationship of executive functions and physical abilities in elite soccer players. *German Journal of Exercise and Sport Research.*

## ABSTRACT

*Objectives:* This study investigated the relationship of executive functions and physical abilities in youth and adult elite soccer players.

*Design/Methods:* 172 elite soccer players (12-34 years of age) performed a computer-based test battery assessing multiple-object tracking, working memory capacity, cognitive flexibility, and inhibition. Another series of tests measured endurance-performance at the individual anaerobic threshold (IAT), ability to repeatedly perform intense exercises (RIEA), and maximal anaerobic performance parameters (squat jump, counter movement jump, drop jump quotient, sprint time).

*Results:* Executive functions and maximal anaerobic parameters showed small to moderate correlations for example, working memory capacity and cognitive flexibility with sprint, countermovement- and drop jump along with a correlation of inhibition and RIEA.

*Conclusion:* These findings favor specific motor-cognition linkages rather than a one-fits-all association. Specifically, sprint and jump seem to be closer linked to cognitive skills than endurance parameters and represent fundamental associations across several age groups.

*Keywords:* cognitive functions, high-performance athletes, physical performance, endurance, motor-cognition

## INTRODUCTION

High-performance team-sport athletes are consistently pushing the limits of human performance under very high pressure. They achieve this by using their outstanding physical abilities (Abade et al., 2014; Murr, Raabe & Höner, 2018) and their superior cognitive skills (for meta-analyses see Voss et al., 2010; Scharfen & Memmert, 2019). However, research at the intersection of sport-psychology, cognitive neuroscience, and sport science is only at the beginning to understand how neural- and cognitive processes are interacting with physical mechanisms to enable athletic peak performance (Huang, Davis, Wolff & Northoff, 2017; Yarrow, Brown & Krakauer, 2009). This initial research predominantly focused on theoretical explanations like the connection of neural pathways related to motor and cognitive processes (Leisman et al., 2016; Gao et al., 2018) while behavioral data of these interactions are scarce and the combination of both cognitive and physical performance in a sample of youth and adult elite soccer players has not been examined yet. Therefore, the present study is unique as it aims to expand this preliminary knowledge on the interplay of these disciplines across several age groups.

Elite sport is one of the brain's biggest challenges as it places a range of multifaceted demands on it (Dietrich, 2006; Walsh, 2014). Investigating the achievements of this sporting brain also provides information about human performance of the normal population (Walsh, 2014). More specifically, investigating sporting brains of youth and adult elite soccer players is rewarding and can yield special insights as they are a high-performance cohort although their bodies and especially their brains are not yet fully developed or just finished it not long ago (De Luca et al., 2003; Lucianna et al., 2005). Further, soccer is of common interest as it is a largescale phenomenon with 265 million players around the world (FIFA, 2013) and the demand profile of a soccer player provides a multifaceted mixture of physical (general- and specific endurance and maximal anaerobic performance) and cognitive demands (executive functions and multiple object-tracking) (e.g. Murr, Feichtinger, Larkin et al., 2018; Murr, Raabe, Höner, 2018; Huijgen et al., 2015; Verburgh et al., 2016).

One research area of this elite sport intersection investigates the executive functions which are a crucial subgroup of basic cognitive functions. Executive functions are defined as cognitive processes that regulate thought and action, especially in nonroutine situations (Friedman et al., 2014). They consist of working memory, cognitive flexibility, and inhibitory control. The predominant neural structure regulating these executive functions is the prefrontal cortex (De Luca et al., 2003; Luciana et al., 2005) with several pathways connecting it to parietal and subcortical brain regions (Darki & Klingberg, 2015; Constantinidis & Klingberg, 2016).

Furthermore, these executive functions are intertwined with physical performance in distinct motor-cognition interactions. The neural basis of these interactions is an overlap in functional brain networks. Specifically, it is argued that the evolution of attention serves successful motor processes and that cognitive functions like working memory have developed to handle motor control (for review see Leisman et al., 2016). From a structural network standpoint this overlap is evident in shared resources. Both, cognitive and motor processes are controlled by a neural collective including the frontal lobe, cerebellum, and the basal ganglia which interact unitedly in order to steer and control executive functions and intentional movements (Leisman et al., 2016; Gao et al., 2018). Regarding the energy usage of these networks the concept of "neural efficiency" indicates that more efficient neural processing (i.e. lower energy usage) is linked to better cognitive performance (Leisman et al., 2016). This mechanism is further based on the finitude of the brain's metabolic resources resulting in a competition of neural processes (Dietrich, 2006). Thus, and in the light of the shared motor-cognition networks, it is possible that this higher neural efficiency in cognitive performance frees up neural working space with a larger amount of energy that can be used for motor planning and execution. This association of better cognitive performance and better motor performance is evident on a behavioral level for young children (i.e. 1,5-13 years of age) (Jansen & Heil, 2010; Lehmann et al., 2014; Gottwald et al. 2016; for review see van der Fels et al., 2015) and on an exploratory level for youth elite soccer players (Scharfen & Memmert, 2019b). However, far more important more research is needed to expand this general association in order to examine specific mechanisms and interplays among certain cognitive and motor skills. As a crucial extension to previous findings the present study aims to analyze this association among skills of both domain that are directly related to sporting performance in a high-performance sample.

Another line of research shows the beneficial effects of physical activity on cognitive functions via cellular/ molecular-, structural/ functional- and also behavioral/socioeconomic changes (Stillman, Cohen, Lehman & Erickson, 2016; Ludyga, Gerber, Pühse et al., 2020), whereas some moderating factors (e.g. level of motor expertise) can also influence these effects (Voyer & Jansen, 2017). However, strong behavioral evidence of these motor-cognition interactions and the influence of physical activity on cognition are scarce in high performing athletes and in age groups ranging from adolescence to adulthood.

Based on the elaborated literature gaps the current study aims to analyze the relationship between domain-general executive functions and domain-general physical abilities in youth and adult elite soccer players. Based on the previous literature it is hypothesized that 1) working memory capacity and 2) cognition total are small to moderately correlated with sprint performance (both 10 and 30 meter). Concerning similar cognitive requirements in both tasks (i.e. shift attention between task sets or strategies) it is hypothesized that 3) cognitive flexibility is small to moderately correlated with drop-jump performance. Additionally, due to previous findings suggesting an important role of inhibition in endurance performance (Martin et al., 2016) it is hypothesized that 4) inhibition is small to moderately correlated with the endurance parameters (i.e. performance at the individual anaerobic threshold and ability to repeatedly perform intense exercises). All other executive functions and physical abilities are studied on an exploratory basis.

Furthermore, executive functions (i.e. working memory, cognitive flexibility, inhibition) and attention (multiple-object tracking) are analyzed based on their crucial role in elite soccer players (executive functions: Verburgh et al., 2014, 2016; Huijgen et al., 2015; Vestberg et al., 2012; Vestberg et al., 2017; for meta-analysis see Scharfen & Memmert, 2019; multiple-object tracking: Faubert, 2013; Romeas et al., 2016). Physical abilities are examined in terms of endurance performance: during an incremental field test (i.e. performance at the individual anaerobic threshold (IAT) and during the YoYo intermittent recovery test (i.e. maximal performance stage stating ability to repeatedly perform intense exercises (RIEA)). As well as in terms of maximal anaerobic performance: during vertical jumps (i.e. squat jump, counter movement jump, drop jump) and during a 30-meter sprint. These measurements are included as they are important performance aspects of high-level team sports like soccer (Unnithan et al., 2012; Waldron & Murphy, 2013; Abade et al., 2014; Murr et al., 2018; RIEA: for review see Bangsbo, Iaia & Krustrup, 2008). But as an important expansion, all of the cognitive and physical parameters are included in one single investigation for the first time. Moreover, we are following the call of Leisman et al. (2016) and aim to extend previous findings (Scharfen & Memmert, 2019b) in a similar study design with a larger population including several age groups. Thus, integrating numerous age groups may also evaluate for the first time if motor-cognition relationships are present across all tested age groups.

Consequently, it could be analyzed whether fundamental associations exist for athletic expertise (in this case soccer) at several developmental phases.

## Methods

### Participants

A total of 172 male elite soccer players (12 – 34 years of age) from the talent development program of the youth academy and the first team of a professional German soccer club were recruited. The following list shows how many players were included per team: U13: 18, U14: 22, U15: 20, U16: 21, U17: 19, U19: 22, U23: 23, first team: 27. However, the dataset was not complete for all of the 172 players as some performance data were missing (i.e. counter-movement jump, drop jump: 4.6%; selective attention, cognition score: 23.7%; sprint (10 and 30-meter; measured during the same run): 31.3%; RIEA, squat jump: 55%; performance-IAT: 65.6%) due to injuries, illness or other absence reasons. Nevertheless, a power analysis indicated that an effect of 0.3 can be detected with a statistical power of .9 at $\alpha = 0.05$ with $n = 112$. At the time of data collection, their teams were playing at the top level of their respective age group (U13, U14, U15, U16, U17, U19, first team) or at the fourth-highest senior league (U23 team). Participants were not diagnosed with any behavioral, learning, or medical conditions that might influence cognitive abilities. The study was carried out in accordance with the Helsinki Declaration of 1975 and was approved by the ethics committee of the local University.

### Procedure and Materials

Cognitive test data were collected in a separate and quiet room. The cognitive test session consisted of one session lasting approximately 45 minutes and was conducted before a soccer training. A battery of four tasks was used to explore individual differences in executive functions. Each task included practice trials in the beginning and is described below. The order of the tests was fixed for all participants, which is a standard method in neuropsychological assessment: 1) multiple-object tracking, 2) working memory, 3) cognitive flexibility, 4) inhibition. All participants were instructed to sit in a comfortable position leaning against the backrest of the chair so that the distance to the screen was the same for all the players. One experienced sport scientist tested all players in a standardized process. Physical performance data were collected on a separate date and are described in detail below. All cognitive and physical data were obtained during the first three weeks of the season 2020/201. The reason for the differing number of participants contributing to the individual correlations is that not every test of physical performance was conducted in every age group. Test leaders of that test battery were experienced sport scientists and athletic coaches.

**Executive Function Tests.**

*Working Memory Capacity* (WMC) was measured by using the well-established working memory span test by Conway, Kane, Bunting, Hambrick, Wilhelm & Engle (2005). It measures the athlete's ability to direct attention toward the current task without getting distracted by other thoughts. More specifically, a counting span task was used (see Kane et al., 2004 for a detailed description), as the simplicity of this processing task makes it usable for almost any type of participant (Conway et al., 2005). The instructions were presented as written text on the computer screen. The counting span task involved counting specific shapes among distractors and then remembering the count totals for later recall. Each stimulus display contained randomly arranged dark blue circles, green circles, and dark blue squares. The task of the participants was to count aloud the dark blue circles and then name the total count aloud at the end. A recall mask occurred after 2–7 stimulus displays into which participants had to fill their memorized count totals in the exact order they had been displayed in. The participants counting span score was a partial credit load score (cf. Conway et al., 2005) which represents the sum of all correctly recalled elements – whereby a correctly recalled item from a set containing two items receives 2 points, and a correctly recalled item from a set with 7 items receives 7 points – divided by the maximum possible score. The test consisted of 15 trials. The dependent measure was the score of correctly memorized objects in percentage representing the working memory capacity (Scharfen & Memmert, 2019b).

*Cognitive Flexibility* was measured with the Trail Making Test (TMT) which consisted of two parts (A and B) (Sánchez-Cubillo, Periáñez, Adrover-Roig, Rodríguez-Sánchez Ríos-Lago, Tirapu & Barceló, 2009). The TMT-A consists connecting numbers in an ascending order and is regularly applied to assess basic visuo-perceptual abilities whereas TMT-B includes the same task as A while also adding letters which requires the participant to switch between both. This part B is used to assess cognitive flexibility (Crowe, 1998). A smaller B-A difference suggests better cognitive flexibility (for detailed a description see Huijgen et al., 2015). A validated tablet version of the TMT was used which has been shown to be congruent with the traditional pen-paper version (Delbaere & Lord, 2015).

*Inhibition* was measured with a computer-based language-independent Stop-Signal Task (SST) from the Cambridge Neuropsychological Test of Automated Battery (CANTAB; Cambridge Cognition 2019). Essentially, the player's response inhibition was tested by asking them to take part in two opposing tasks: a Go task and a Stop task. They were instructed to press a left-hand button when an arrow appeared which pointed to the left, and a right-hand button when the arrow pointed right (i.e. Go task in 75% of trials). Contrary, they should inhibit the response and not press any buttons when they heard an auditory 'beep' signal (i.e. Stop task in 25% of trials). The onset of the 'beep' signal varied depending on a staircase protocol (i.e. either decreased or increased) based on whether their previous trial was successful or not. The dependent variable is the Stop-Signal Reaction time (SSRT) in which a higher value indicates poorer inhibitory control (Fogel et al., 2019). More detailed information about the test protocol has been described elsewhere (Fogel et al., 2019).

*Multiple-Object Tracking* was analyzed with the NeuroTracker 3D-MOT task with the NeuroTracker™ Core Program by CogniSens Athletics Inc. from the University of Montreal. The program was depicted on a wall via a video projector. Essentially, the task consisted of eight balls of which four are highlighted for two seconds. Then, the four highlighted balls needed to be tracked for 8 seconds. Afterwards, the tracked balls needed to be stated in to analyse the performance. Further settings were the same as in Faubert (2013).

The value Cognition-Total was calculated by adding the z-standardized scores of all cognitive tests and dividing the sum by the number of included tests.

### Physical Tests

The *Individual Anaerobic Threshold (IAT)* represents the highest exercise intensity that can be sustained for a prolonged period without lactate substantially building up in the athlete's blood. IAT was measured with an incremental field test following the protocol of Faude et al. (2014) with the difference that the protocol was the same for every player - starting speed was 9 km/h and speed of the last stage was 16.5 km/h. A recovery round (i.e. 400m by 6 km/h) followed this last stage. Specifically, the parameter heart-rate-recovery reflects the dynamic balance between parasympathetic nervous system reactivation and sympathetic nervous system withdrawal (HRR; by calculating the percentage of heartrate after the recovery round related to the maximal heartrate) and was included based on Schneider et al. (2018) and Buchheit (2014).

*Vertical jump performance* was measured with (1) countermovement jump , (2) squat jump, (3) drop jump (box height = 35 cm) by using a contact mat (SmartJump; Smartspeed, Fusion Sport, Australia). The protocol of Faude et al. (2014) was followed except for jumping with arm usage in order to reflect soccer specific demands. Dependent measures for counter-movement jump and squat jump was height and a quotient for drop jump which is the calculated relation of height and contact time.

*Sprint performance* was measured using infrared timing gates (Smartspeed, Fusion Sport, Australia). Players were instructed to run as fast as possible through the gates on a 30-meter distance. The protocol of Faude et al. (2014) was followed with the difference that the starting line was 0.5 meter behind the first timing gate, the resting time in between the 3 trials per player was 3 minutes and only the best 30-meter time was used as the dependent variable.

The *ability to repeatedly perform intense exercises (RIEA)* was measured with the YoYo intermittent recovery test level 1 by following the protocol of Krustrup et al., (2003).This protocol includes repeated 2x20-m runs back and forth between the starting, turning, and finishing line at a progressively increased speed controlled by audio bleeps from a tape recorder. All tests were conducted on a soccer pitch with artificial grass and players completed a standardized warm-up before starting the test. Excellent reliability and validity are reported for this test (Krustrup et al., 2003; Deprez et al., 2014). The dependent variable is the maximal reached performance stage.

### Statistical Analysis

Data were analyzed using IBM SPSS Statistics 26.0.0. Based on the exploratory nature of this examination, instead of conducting null-hypothesis significance tests, current recommendations to focus on estimation for best reporting and analysis practice were followed (Cumming, 2014); effect-sizes with 95% confidence intervals are reported. The variables were not normally distributed, as assessed by Shapiro-Wilk's test ($p > 0.05$). Therefore, the Speaman's correlation coefficient test was used to investigate the correlation between the player's cognitive and physical performance. Correlation coefficients (Pearson's *r*) of 0.1, 0.3, and 0.5 represent small, moderate, and large effect size estimates respectively (Cohen, 1998). In order to control for the only team which was not playing at the highest level of their respective age group (i.e. U23) a separate correlation analysis was conducted without that team to examine possible differences.

## Results

Correlations (Pearson's r) with their 95 % confidence intervals and the sample sizes contributing to each correlation among the executive functions and physical abilities whilst controlling for age are stated in Table 1. Additionally, bivariate correlations are stated in Table 2. Sprint (10- and 30-meter) performance shows small to moderate correlations with working memory capacity, cognitive flexibility, Cognition-Total and a negative correlation with inhibition. Squat jump is moderately correlated with inhibition and further small to moderate correlations are present among drop jump and cognitive flexibility and countermovement jump and working memory capacity. The RIEA parameter is small to moderately correlated with inhibition.

*Table 1.* Partial correlations between executive functions and physical abilities whilst controlling for age group

| | Performance -IAT | Sprint (10m) | Sprint (30m) | SJ | CMJ | DJQ | RIEA |
|---|---|---|---|---|---|---|---|
| Working Memory | | | | | | | |
| Spearman's *r* | 0.09 | **-0.33** | **-0.24** | 0.17 | **0.19** | 0.11 | 0.20 |
| CI | -0.22, 0.37 | **-0.5, -0.15** | **-0.41, -0.05** | -0.10, 0.41 | **0.01, 0.40** | -0.07, 0.27 | -0.07, 0.44 |
| *n* | 42 | **103** | **103** | 56 | **122** | 122 | 56 |
| Cognitive Flexibility | | | | | | | |
| Spearman's *r* | | | | | | | |
| CI | 0.17 | **0.23** | **0.20** | 0.13 | -0.05 | **-0.27** | 0.11 |
| *n* | -0.14, 0.45 | **0.04, 0.41** | **0.01, 0.38** | -0.14, 0.38 | -0.23, 0.13 | **-0.43, -0.10** | -0.16, 0.35 |
| | 42 | **103** | **103** | 56 | 122 | **122** | 56 |
| Inhibition | | | | | | | |
| Spearman's *r* | 0.25 | -0.01 | **-0.23** | **0.55** | 0.09 | 0.10 | **0.28** |
| CI | -0.06, 0.51 | -0.20, 0.17 | **-0.41, -0.04** | **0.34, 0.71** | -0.09, 0.25 | -0.08, 0.26 | **0.02, 0.51** |
| *n* | 42 | 103 | **103** | **56** | 122 | 122 | **56** |
| Included teams | U16-U19 | U13-U23 | U13-U23 | U15-U19 | U13-first team | U13-first team | U14-U19 |
| MOT | | | | | | | |
| Spearman's *r* | 0.04 | 0.01 | -0.08 | 0.02 | 0.07 | -0.09 | 0.01 |
| CI | -0.27, 0.34 | -0.22, 0.24 | -0.31, 0.15 | -0.24, 0.28 | -0.14, 0.27 | -0.29, 0.12 | -0.28, 0.31 |
| *n* | 42 | 72 | 72 | 56 | 91 | 91 | 42 |
| Cognition Total | | | | | | | |
| Spearman's *r* | 0.04 | **-0.24** | -0.06 | 0.06 | 0.06 | 0.03 | 0.04 |
| CI | -0.27, 0.34 | **-0.45, -0.01** | -0.29, 0.17 | -0.21, 0.32 | -0.15, 0.26 | -0.18, 0.23 | -0.27, 0.34 |
| *n* | 42 | **72** | 72 | 56 | 91 | 91 | 42 |
| Included teams | U16-U19 | U15-U23 | U15-U23 | U15-U19 | U15-first team | U15-first team | U15-U19 |

*Note.* IAT: individual anaerobic threshold, SJ: squat jump, CMJ: counter-movement jump, DJQ: drop jump quotient, RIEA: ability to repeatedly perform intense exercises, MOT: multiple-object tracking; meaningful correlations are highlighted with bold numbers

# DISCUSSION

The current study aimed to investigate the performance of the sporting brain of youth elite athletes, more specifically the relationship between executive functions and physical abilities in youth and adult elite soccer players. In general, numerous small, moderate, and large correlations with differing confidence intervals based on the differing sample sizes were present among these skills. The fact that some results show no correlation at all indicates that there is no one-fits-all explanation for the linkages of cognitive- and physical skills but rather that they are very specific which contradicts our second hypothesis. Namely, findings show for the first time that maximal anaerobic parameters seem to be closer linked to cognitive skills than endurance parameters. Further, working memory capacity and cognitive flexibility seem to have the most consistent connection to the maximal anaerobic parameters sprint and jump which confirms and even extends our hypothesis 1 and 3. This apparent association is in alignment with motor-cognition interactions based on structural and functional brain networks (Leisman et al., 2016; Gao et al., 2018; Darki & Klingberg, 2015; Constantinidis & Klingberg, 2016; Ptak, Schnider & Fellrath, 2017; Hanakawa, 2011), the beneficial effects of physical activity on cognition (Stillman et al., 2016; Ludyga et al., 2020) as well as with behavioral evidence of this motor-cognition interaction in children (Jansen & Heil, 2010; Lehman et al., 2014; Gottwald et al. 2016; van der Fels et al., 2015). Preliminary findings in youth elite soccer players showing associations of working memory capacity and sprint as well as ball handling motor skills (e.g. dribbling) (Scharfen & Memmert, 2019b) are expanded by the present study concerning the maximal anaerobic parameters. However, far more important, the individual areas of physical performance are further discussed in the following sections.

## Endurance performance

The only meaningful association of endurance parameters and executive functions was present in RIEA correlating small to moderately with inhibition implying a poorer endurance performance in players with better inhibition. However, the present results are contrary to our fourth hypothesis and previous literature as it suggests that a self-determination of the maximal performance stage, which is part of the RIEA, is stronger interconnected with cognitive processes and especially inhibition (Blanchfield et al., 2014). However, pure capacities of endurance performance do not necessarily equal the optimal and effective usage of that capacities in terms of correct running paths in game situations. Since the present study examined the subcategory response inhibition defined as the inhibition of behavior (Diamond, 2013), it is also possible that players with better response inhibition use their endurance capacities more effectively as they are eventually able to inhibit unnecessary running paths or sprints. Consequently, the lower workload would result in poorer endurance capacities (Malone et al., 2019). The large effect of age on this correlation seems plausible and confirms previous studies as both parameters mature with increasing age (Beavan, Chin, Ryan et al., 2020; Ford, de Ste Croix, Ford et al., 2011). Nevertheless, the absence of any other meaningful correlations may also be based on the relatively small differences in this comparably homogenous sample of elite athletes.

### Maximal anaerobic performance

Linear sprint was meaningfully correlated with working memory, cognitive flexibility and cognition total (only 10-meter time) whilst controlling for age which confirms hypothesis 1 and extends assumptions of hypothesis 3. This is in line with the argument that working memory has developed with the special purpose to handle motor control (Leisman, 2016). Since the sprint is one of the movements with the highest loads and intensities on the neuromuscular system (Malone, Owen, Mendes et al., 2018) a better working memory capacity could therefore result in a sophisticated neuromuscular coordination leading to a better sprint performance. In addition, cognitive flexibility also seems to contribute to a better sprint performance possibly based on the extremely rapid change of highly differing motor patterns. Specifically, the switching from a standing situation with no movement to explosively run as fast as possible with very high loads and intensities on the neuromuscular system (Malone, et al., 2018). Since both correlations (i.e. working memory capacity, cognitive flexibility) are larger in the 10-meter compared to the 30-meter time the beginning of the sprint may require higher attentional capacities to execute the start of the complex and explosive neuromuscular coordination whereas this explosive aspect is attenuated with increasing velocities and distances (Bezodis, Willwacher & Salo , 2019). Importantly, these correlations seem to be present across all developmental stages (i.e. all tested age groups) as age had no meaningful effect on them. This might significantly expand previous findings and indicate a fundamental linkage inherent to the athletic expertise at all included phases of age. Lastly, the negative correlation between inhibition and sprint (30-meter time) could also be based on the previously hypothesized more effective usage of physical capacities resulting in lower workloads of players with better inhibition could also explain the present association. However, as the current findings on this relationship are the first of its kind the explanation is rather speculative than based on descriptive data.

Moreover, age had a moderate influence on these correlations of sprint and cognition which could be based on an activity-dependent maturation of the central nervous- and musculoskeletal system (Fields, 2015). Specifically, as players extensively repeat the movement as a function of age their cognitive control of sprints may decrease as the degree of movement automatization may increase. This could result in higher neural efficiency (Leisman, 2016) and thus, attenuate the intensity of the relationship (van der Fels et a., 2015). Further influences may also be originated in the development of the muscular system due to progressing puberty and related male sex hormones.

For the first time certain correlations of executive functions and vertical jump performance are present as well. Firstly, working memory capacity correlates small to moderately with countermovement jump which is again in agreement with the statement that working memory's evolutionary main purpose is controlling motor actions (Leisman, 2016). Further, it also extends assumption of our first hypothesis Additionally, the constant execution of such a maximal anaerobic movement in soccer training and games could also result in an increased working memory capacity representing a bidirectional effect which may confirm a) suggestions that both motor and cognitive functions develop from a common source and a single motive: to control action (Gottwald et al., 2016; van der Fels et al., 2015) and b) the positive influence of physical activity, especially coordination on cognition (Ludyga et al., 2020). Again, age moderately influenced the associations of working memory capacity and countermovement jump as well as squat jump which could also be based on previously described processes like activity-dependent maturation of the central nervous system and further development of the musculature.

Secondly, the correlation of cognitive flexibility and drop jump quotient may be explained by the similar requirements of the tasks which confirms our third hypothesis. Cognitive flexibility is defined as the ability to shift attention between task sets or strategies (Myiake et al., 2000).

Therefore, a sophisticated performance of this ability could also enable a better drop jump quotient performance as a quick and explosive switch between two different motor programs (i.e. stepping downwards vs jumping upwards), representing different task sets or strategies required in this task.

Lastly, the association of inhibition of and squat jump indicates a poorer jumping performance in players with better inhibition. Since squat jump- and sprint performance are closely linked to each other (Köklü, Alemdaroğlu, Özkan et al., 2015) this association could be explained by the positioning of physically faster players at winger positions. However, this is rather speculative as it cannot be based on descriptive data.

In general, the current findings confirm the small to moderate correlation of working memory capacity and sprint (Scharfen & Memmert, 2019b). But as an important extension, it is remarkable that the unique relationship between executive functions and maximal anaerobic performance seems to exist across all included teams as age had no substantial effect on the correlation. Again, this could hint at a central association integral to athletic expertise at several developmental phases. However, although the sample size of that preliminary study is much smaller (i.e. 15) the results indicate that working memory capacity is especially associated with more complex motor tasks like dribbling or ball control which is in agreement with findings of a recent meta-analysis indicating that coordinative exercise is more beneficial for cognition than resistance or endurance activities (Ludyga et al, 2020).

## Conclusion

The current results of the relationship between executive functions and physical abilities in elite soccer players consist of numerous small, moderate, and large correlations among these skills. A one-fits-all association does not seem to exist but rather very specific linkages among cognitive- and physical skills are present for the first time. From a practical standpoint these motor-cognition associations suggest applying a more holistic approach when working with physical performance data. Taking executive functions into consideration as well seems to have the potential to increase the understanding of the player's performance and may ultimately lead to options to increase this performance. However, more research is needed to establish the effects of possible options like cognitive training on physical performance.

## Limitations

Some limitations of the present study also need to be acknowledged. First of all, as with all correlational analysis the current associations are not equally conclusive as longitudinal causality analysis. Furthermore, both cognitive- and physical performance data are not completely existent for every player which decreases statistical power and increases the lengths of confidence intervals of some correlations. Additionally, covariates like socioeconomic- and intelligence level were not analyzed and need to be included in future studies and the tests also lack soccer-specificity. It is also important for future research to examine generalization of this findings with female soccer players.

### Outlook

Consequently, future studies are required to evaluate whether these motor-cognition associations are causal in nature. This could be achieved by analyzing transfer effects of training certain motor or cognition aspects. If such transfers effects occur, it may also be worthwhile to investigate whether they are more distinctive in certain age groups. Furthermore, examining 1) more complex motor tasks of dynamic soccer situations (e.g. small sided games) and 2) actual match performance for example passing accuracy or failures resulting in turnovers are absolutely vital to further improve the understanding of this connection.

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## Appendix III.I Bivariate correlations between executive functions and physical abilities

| | Performance-IAT | Acceleration (10m) | Sprint (30m) | SJ | CMJ | DJQ | RIEA |
|---|---|---|---|---|---|---|---|
| Working Memory | | | | | | | |
| Spearman's *r* | 0.09 | **-0.43** | **-0.36** | **0.30** | **0.35** | 0.15 | **0.36** |
| CI | -0.21, 0.37 | **-0.57, -0.26** | **-0.52, -0.18** | **0.05, 0.52** | **0.19, 0.50** | -0.03, 0.32 | **0.11, 0.56** |
| *n* | 45 | **106** | **106** | **59** | **125** | 125 | **59** |
| Cognitive Flexibility | | | | | | | |
| Spearman's *r* | 0.11 | **0.36** | **0.34** | -0.04 | **-0.27** | **-0.29** | -0.18 |
| CI | -0.19, 0.39 | **0.18, 0.52** | **0.16, 0.50** | -0.29, 0.22 | **-0.43, -0.10** | **-0.44, -0.12** | -0.42, 0.08 |
| *n* | 45 | **106** | **106** | 59 | **125** | **125** | 59 |
| Inhibition | | | | | | | |
| Spearman's *r* | 0.07 | **0.40** | **0.38** | 0.11 | **-0.43** | 0.04 | **-0.32** |
| CI | -0.23, 0.36 | **0.23, 0.55** | **0.20, 0.53** | -0.15, 0.36 | **-0.56, -0.28** | -0.14, 0.21 | **-0.53, -0.07** |
| *n* | 45 | **106** | **106** | 59 | **125** | 125 | **59** |
| Included teams | U16-U19 | U13-U23 | U13-U23 | U15-U19 | U13-first team | U13-first team | U14-U19 |
| MOT | | | | | | | |
| Spearman's *r* | 0.10 | -0.20 | **-0.28** | 0.16 | **0.27** | -0.06 | 0.23 |
| CI | -0.2, 0.38 | -0.41, 0.03 | **-0.48, -0.06** | -0.10, 0.40 | **0.07, 0.45** | -0.26, 0.14 | -0.07, 0.49 |
| *n* | 45 | 75 | **75** | 59 | **94** | 94 | 45 |
| Cognition Total | | | | | | | |
| Spearman's *r* | -0.03 | -0.01 | 0.05 | 0.01 | -0.04 | 0.02 | -0.05 |
| CI | -0.32, 027 | -0.24, 0.22 | -0.18, 0.27 | -0.25, 0.27 | -0.24, 0.16 | -0.18, 0.22 | -0.34, 0.25 |
| *n* | 45 | 75 | 75 | 59 | 94 | 94 | 45 |
| Included teams | U16-U19 | U15-U23 | U15-U23 | U15-U19 | U15-first team | U15-first team | U15-U19 |

*Note.* IAT: individual anaerobic threshold, SJ: squat jump, CMJ: counter-movement jump, DJQ: drop jump quotient, RIEA: ability to repeatedly perform intense exercises, MOT: multiple-object tracking; meaningful correlations are highlighted with bold number

## Appendix IV: Publication IV

# Fundamental relationships of executive functions and physiological abilities with game intelligence, game time and injuries in elite soccer players

**Reference:**

Scharfen, H. E., & Memmert, D. (2021). Fundamental relationships of executive functions and physiological abilities with game intelligence, game time and injuries in elite soccer players. *Applied Cognitive Psychology*.

# ABSTRACT

The study examined the (1) interrelation of cognitive-athletic performance concerning game time and (2) injuries; (3) relation between executive functions and game intelligence. A total of 172 elite soccer players (age: 12–34 years) performed tests assessing multiple-object-tracking, working memory capacity (WMC), cognitive flexi- bility (CF), and inhibition. General and specific-endurance-performance, and physical performance (jumps and sprint) were also measured. Game intelligence, time and injuries were tracked. WMC, CF, and a total cognition score showed correlations with game intelligence, and the same parameter, along with selective attention and game intelligence were also correlated with game time. Sprint and specific-endurance were connected with game time, whereas contact injuries only correlated with sprint, and noncontact injuries with sprint and general-endurance. Especially executive functions represent fundamental associations with game intelligence and -time across all age groups, whereas certain physiological abilities may contribute to more game time and less non-contact injuries depending on age.

*Keywords:* cognitive functions, high-performance athletes, physiological performance, talent prediction

## INTRODUCTION

The prediction of talent across all ages is a crucial aspect of high- performance settings (Coulson-Thomas, 2012). One of these settings is team sports like elite soccer, where certain physical, physiological and cognitive skills are required to operate on an extraordinary level (Memmert, 2021). Identifying the principal mechanisms of high- performance of all age groups in this sport is of common interest as soccer is a largescale phenomenon with 265 million players around the world (FIFA, 2013). Hence, soccer associations and clubs need to find the players among the large amount with certain characteristics enabling them to succeed later or currently in their career on a professional level. However, the extent to which a combination of physiological and cognitive skills contributes to success in elite soccer is still unclear (Rein & Memmert, 2016; Murr, Feichtinger, et al., 2018; Murr, Raabe, & Höner, 2018; Williams et al., 2020). Thus, the present study is unique as it aims to examine the effect size of the contribution of both abilities to success of youth as well as adult elite soccer players. Though, previous studies examined how certain objective performance parameters may contribute to success in isolation. The majority of these investigations had a monodisciplinary focus on physical (e.g., height and weight) or physiological (e.g., endurance and speed) determinants whereby the latter has been partially related to success in soccer (for reviews see Murr, Raabe, & Höner, 2018; Williams et al., 2020). However, it is well-known that success in a complex game like soccer depends on multidisciplinary, symbiotic aspects which need to be investigated in study designs which represent that multi- disciplinarity according to best practice guidelines (Baker et al., 2020; Johnston et al., 2018; Rees et al., 2016; Till & Baker, 2020; Williams et al., 2020). However, these guidelines have rarely been applied in previous studies (Johnston et al., 2018; Williams et al., 2020) whereas first evidence indicates that physiological and cognitive skills may be crucially interrelated (Scharfen & Memmert, 2019b). The expert performance approach—analyzing sports-specific cognition—has already pointed out the relevance of cognition in team sports (Mann et al., 2007). This approach has recently been complemented by the cognitive component skills approach—analyzing domain-general cognition (Scharfen & Memmert, 2019a; Voss et al., 2010). Current models propose that especially the domain-general cognition is an important part of this multi- disciplinarity as well, besides physiological characteristics (Baker et al., 2019; Baker et al., 2020; Johnston et al., 2018; Rees et al., 2016; Till & Baker, 2020; Vaeyens et al., 2009). Thus, recent studies established a promising association to elite performance especially present in soccer (Huijgen et al., 2015; Sakamoto et al., 2018; Scharfen & Memmert, 2019a; Verburgh et al., 2014, 2016; Vestberg et al., 2012, 2017, 2020). These first studies represent an encouraging value of domain-general cognition for talent identification but evidence on their contribution to success in elite soccer, especially across several age groups is scarce as the majority of the investigations had a monophasic focus (i.e., the examination of only one specific phase of development/age group; Ivarsson et al., 2020; Johnston et al., 2018; Sakamoto et al., 2018; Vestberg et al., 2012, 2017, 2020; Williams et al., 2020). Specifically, a crucial subgroup of these cognitive skills are the executive functions defined as cognitive processes that regulate thought and action, especially in nonroutine situations (Diamond, 2013; Friedman et al., 2006; Miyake & Friedman, 2012). They include (i) working memory: holding information in mind and mentally working with it; (ii) cognitive flexibility (CF): changing perspectives or approaches to a problem, flexi- bly adjusting to new demands, rules, or priorities and (iii) inhibitory control: control one's attention, behavior, thoughts, and/or emotions to override a strong internal predisposition or external lure, and instead do what's more appropriate or needed (Diamond, 2013). Furthermore, best practice guidelines also propose the inclusion of coach-rated evaluation which has been rarely conducted previously (Williams et al., 2020). A first attempt to analyze those coach-rated criteria for the cognitive domain showed that the coaches' assessment of game intelligence is moderately correlated with executive functions' objective parameters in adult elite soccer players (Vestberg et al., 2020). Nevertheless, this interrelation has not been shown in adolescents yet, and the extent to which a combination of these coach-rated- and objective cognitive parameters relate to success is still unknown. Another line of research concerning performance data emphasizes that high injury-risks are associated with poor cognitive functioning (Giesche et al., 2020; Monfort et al., 2019; Swanik et al., 2007). However, the association of behavioral data for real injuries and not only injury-risks needs further evaluation (Ivarsson et al., 2017). More specifically, the differentiation between contact and non- contact injuries is relevant due to the contrasting underlying mechanisms and their distinct incidence numbers (Swanik et al., 2007). However, by reviewing the literature on previous endeavors to identify key characteristics of talent and injuries, it becomes evident that the common focus was (1) rarely a combination of cognitive and physical characteristics and (2) monophasic by either focusing on adults or adolescents. Although first investigations of the association between cognitive performance and success in elite soccer are promising this area is still in its infancy and also quite debatable (Beavan et al., 2020). Additionally, the coach-rated assessments of this cognitive performance and its interrelation with objective cognitive parameters are mostly unknown and, previous examinations only included adults. Thus, using a multiphasic focus by integrating both age groups may also evaluate for the first time how large the effects of certain relationships are across all tested age groups. Consequently, it could be analyzed to what extent fundamental associations exist for soccer expertise at every developmental phase. This would yield valuable insights in terms of (a) a performance-needs analysis of current demands of high-performance in complex team sports like soccer and (b) a more sophisticated understanding of the contribution of cognitive and physiological skills of expertise and talent to certain developmental stages (Baker et al., 2019, 2020; Johnston et al., 2018; Till & Baker, 2020). Based on the outlined literature gaps, the aim of the present study on adolescent and adult elite soccer players (i.e., 12–34 years of age) is threefold. First, the multidisciplinary and multiphasic performance data, including physiological and cognitive (objective and coach-rated) parameters, are examined in two regards: (1) as a primary aim in terms of success defined as the playing time per player in games which is a commonly used performance indicator (Rumbold et al., 2020) and (2) as a secondary aim in terms of injury incidence (i.e., contact and non-contact). Further, the extent to which coach- rated game intelligence and objective assessments of executive functions are interrelated is analyzed as an exploratory aim as well as the subgroup comparison of youth and adult players. Moreover, based on previous literature it is hypothesized that (1) a moderate effect of better physiological and cognitive skills on more playing time and (2) fewer injuries exists which is independent of age and (3) game intelligence correlates moderately with executive functions. Taken together, the purpose of the present study is to generate a more holistic understanding of the extent to which executive functions contribute to high-performance sports in terms of success and injury prevention. More specifically, game intelligence, executive functions and attention (multiple-object tracking) are analyzed based on their crucial role in elite soccer (game intelligence Vestberg et al., 2020; executive functions Huijgen et al., 2015; Scharfen & Memmert, 2019a; Verburgh et al., 2014, 2016; Vestberg et al., 2012, 2017; multiple-object tracking (Faubert, 2013; Romeas et al., 2016). Physiological abilities are included as they are important performance properties of high-level game performance (Abade et al., 2014; Bangsbo et al., 2008; Murr, Raabe, & Höner, 2018; Unnithan et al., 2012; Waldron & Murphy, 2013) and are commonly examined in the talent prediction studies of the physiological domain

(Murr, Raabe, & Höner, 2018; Williams et al., 2020). Additionally, we are following several calls (Baker et al., 2020; Johnston et al., 2018; Rees et al., 2016; Till & Baker, 2020; Vestberg et al., 2020; Williams et al., 2020) to conduct multidisciplinary, multi- phasic and longitudinal research including coach-rated assessments and aim to expand previous findings (Vestberg et al., 2020) in a similar study design with a larger population also including adolescents.

## Methods

### Participants

A total of 172 male elite soccer players (12–34 years of age) from the youth academy's talent development program (n = 145) and the first team (n = 27) of a professional German soccer club were recruited. However, the dataset was not complete for all of the 172 players as some performance data were missing either i) at random (missing: CMJ, DJ: 4.6%; game intelligence: 14.6%; selective attention, cognition score: 23.7%; acceleration [5 and 30-meter]: 31.3%; RIEA, SJ: 55%; performance-IAT: 65.6%) due to injuries, illness other absence reasons in those tests that were conducted in certain teams (e.g., RIEA in U14-U19) or ii) systematically as some physical tests were not performed in certain teams (e.g., RIEA in U13, U23 and first-team) as analyzed by Little's missing completely at random (MCAR) test (Little, 1988) which were consequently not included in the further analysis. At the time of data collection, their teams played at the top level of their respective age group (U13 with n = 17, U14 with n = 21, U15 with n = 20, U16 with n = 21, U17 with n = 19, U19 with n = 22, first team with n = 27) or at the fourth-highest senior league (U23 team with n = 24). Participants were not diagnosed with any behavioral, learning, or medical conditions that might influence cognitive abilities. Written informed consent was obtained from every participant or their legal guardian before commencing the tests. The study was carried out by the Helsinki Declaration of 1975 and was approved by the ethics committee of the German sports university cologne. Executive functions are analyzed in terms of working memory, CF, inhibition, and attention is investigated by multiple-object tracking. Physiological abilities are examined in terms of endurance performance with an incremental field test (i.e., performance at the individual anaerobic threshold (IAT) and a YoYo intermittent recovery test (i.e., maximal performance stage stating the ability to perform intense exercises repeatedly [RIEA]). As well as in terms of physical performance: with vertical jumps (i.e., squat jump (SJ), counter- movement jump (CMJ), drop jump (DJ)), and with a 30-m sprint.

## Procedure and materials

Data of cognitive tests were collected in a quiet room. The cognitive tests consisted of one 45-minute session and were conducted before a training session with a sufficient familiarization period (i.e., explanation with test trials) for every measurement. A four-task battery was used to explore the performance of executive functions. Each task started with practice trials in the beginning and is described below. Fixed test order was used, a standard method in neuropsychological assessment: (1) working memory, (2) CF, (3) inhibition and (4) multiple-object tracking. All participants were asked to sit in a comfortable position leaning against the backrest of the chair so that the screen distance was the same for all the players. Physiological performance data were collected on a separate session and are described in detail below. All cognitive and physical data were obtained during the first 3 weeks of the season 2020/2021. The reason for the differing sample sizes contributing to the individual correlations is that not every test was conducted in every age group due to the constraints of the club's organization. Leaders of the test batteries were experienced sport scientists and athletic coaches. Nevertheless, this does not change the possible valuable insights generated from this study as the results are interpreted along with their confidence intervals, effect sizes and contributing sample size which allows for comparison of findings even among differing sample sizes (Cumming, 2014).

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**Executive function tests.** *Working memory capacity* (WMC) was measured using the well-established working memory span test by Conway et al. (2005). It measures the player's skill to direct attention toward the present task with- out getting distracted by other thoughts. More precisely, a counting span task was applied (see Kane et al., 2004 for a detailed description), as this processing task's simplicity allows a widespread application (Conway et al., 2005). The instructions were presented as written text on the computer screen. The counting span task was to count specific shapes among distractors and afterward remembering the count totals for later recall. Every stimulus image included randomly arranged dark blue circles, green circles, and dark blue squares. The task of the participants was counting the dark blue circles and then the total count at the end. A recall mask was presented after 2–7 stimulus images into which participants had to fill their memorized count totals in the exact order they had been illustrated in. The participants counting span score was a partial credit load score (cf. Conway et al., 2005), which represents the sum of all correctly recalled elements—whereby a correctly remembered piece from a set containing two elements receives 2 points, and a correctly remembered element from a set with 7 items receives 7 points—divided by the maximum possible score. Good reliability and validity are stated for the test (ICC = 0.7–0.9; Conway et al., 2005). The test included 15 trials. The dependent measure was the score of correctly memorized objects in percentage representing the WMC (Scharfen & Memmert, 2019b).

*Cognitive Flexibility* was measured with the trail making test (TMT) including two parts (A and B) (Sánchez-Cubillo et al., 2009). The TMT-A is commonly used to measure visuo-perceptual abilities whereas TMT-B is used to assess CF (Crowe, 1998). A smaller B-A difference indicates better CF (for a detailed description see Huijgen et al., 2015). A validated tablet version of the TMT was used, which is congruent with the traditional pen-paper version (Delbeare & Lord, 2015). General validity and reliability of the TMT are high (Cronbach's alpha = 0.9; ICC = 0.86–0.94; Smith et al., 2008; Wagner et al., 2011).

*Inhibition* was assessed with a computer-based language-independent stop-signal task (SST) from the Cambridge Neuropsychological Test of Automated Battery (CANTAB; Cambridge Cognition 2019). The participant's response inhibition was essentially measured by asking them to take part in two opposing tasks: a Go task and a Stop task. They were instructed to press a left-hand button when an arrow occurred which pointed to the left, and a right-hand button when the arrow pointed right (i.e., Go task in 75% of trials). Addition- ally, they were instructed to inhibit the response and not press any buttons when they heard an auditory "beep" signal (i.e., Stop task in 25% of trials). The onset of the "beep" signal varied in dependence on a staircase protocol (i.e., either decreased or increased) which was based on their performance in the previous trial. The dependent variable is the stop-signal reaction time (SSRT) which is an estimate of the time a participant needed to stop his or her response minus the mean delay, with shorter SSRTs indicating better inhibitory control (Matzke et al., 2018). More detailed information about the test protocol has been described previously (Matzke et al., 2018). SSRT is highly reliable (split-half reliability = 0.91; Williams et al., 1999). *Multiple-Object Tracking* was analyzed with the NeuroTracker 3D-MOT task with the NeuroTracker™ Core Program by CogniSens Athletics Inc. from the University of Montreal. The program was displayed on a wall via a video projector. The task included eight balls of which four are marked for 2 s. Then, the four marked balls needed to be tracked for 8 s. Afterward, the tracked balls are required to be stated to analyze the performance. Other settings were the same as in Faubert (2013). The value cognition-total was calculated by adding the z-standardized scores of all cognitive tests and dividing the sum by the number of included tests.

**Assessment of game intelligence.** The head coaches of each team (i.e., eight in total) were asked to judge their players' game intelligence compared to what they perceive as the average level of their respective league and age group (e.g., German Bundesliga for the first team) as a questionnaire on a one-item assessment. Similar to a previous study, a stanine-scale was used with 5 representing the average of their league and age group, 1 is the lowest and 9 the highest value (Vestberg et al., 2020). Again, similar to Vestberg et al. (2020) no predefined definition of game intelligence was stated as there is no exact definition (Stratton et al., 2004; Wein, 2004) but professional coaches of elite teams have a homogenous and robust opinion of its compounds and level in players. Accordingly, we inferred that their evaluations may be an appropriate measure of player's game intelligence level. Further, to ensure the objectivity of this game intelligence evaluation the ratings of the sports director of the respective age groups were analyzed as well and in addition to the ratings of the coaches of the team. A high degree of inter-rater reliability among the ratings of the sports directors and the respective coach was present as the average measure ICC was 0.82.

**Physiological tests.** A sufficient familiarization period (i.e., explanation with test trials) was conducted before every measurement.

The *IAT* represents the maximal exercise intensity that can be sustained for a continued period without lactate substantially building up in the athlete's blood. IAT was assessed with a staircase-field test following the protocol of Faude et al. (2014) with the difference that the proto- col was the same for every player - initial speed was 9 km/h and speed of the last stage was 16.5 km/h. Running speed was increased every 3 min by 2 km/h and the test was terminated when participants were not able to follow the given speed anymore. To determine the IAT, capillary blood samples (20 µl) were taken from an earlobe at rest and during 30-second breaks between stages and at 1, 3, 5, 7 (Faude et al., 2014). High reliability and and validity are stated for this test (González-Haro et al., 2007).

*Vertical jump performance* was assessed by (1) countermovement jump (CMJ), (2) squat jump (SJ), (3) drop jump (DJ) (box height = 35 cm) on a contact mat (Smart Jump; Smart speed, Fusion Sport, Australia). The protocol of Faude et al. (2014) was applied except for jumping with arm usage to represent soccer-specific demands. Excel- lent reliability and validity are stated for this test (ICC = 0.99; Rodriguez-Rosell et al., 2016). Dependent measures for CMJ and SJ were height and a quotient for DJ (i.e., DJQ), the calculated relation of height and contact time which were measured using a contact mat with the electrical signal transmitted to a personal computer (Smart speed, Fusion Sport, Australia).

*Sprint performance* was assessed with infrared timing gates (Smartspeed, Fusion Sport, Australia). The protocol of Faude et al. (2014) was applied with a starting line 0.5 m behind the first timing gate whereby resting time was 3 min and only the best 5- and 30-m time was included as the dependent variable. For each player, testing con- ditions were constant intraindividual. The repeated intense exercise ability (RIEA) was assessed with the YoYo intermittent recovery test level 1 by following the protocol of Krustrup et al. (2003) and consisted of 2 x 20-m runs back and forth between the starting, turning, and the finishing line at a progressively increased speed administered by audio beeps from a tape recorder. All tests were applied on a soccer pitch with artificial grass, and players conducted a standardized warm-up before starting the test. Excellent reliability (ICC = 0.98) and validity are stated for this test (Deprez et al., 2014; Krustrup et al., 2003). The dependent variable is the maximal reached performance stage.

**Game time.** Game time was evaluated during the beginning of the season 2020/2021 till the end of October, resulting in a minimum of three and a maximum of eight games per team. The reason for this cut-off was the ceasing of the regular soccer leagues. Game time for each player was noted by using the club-internal data records. To gain a standardized game time score for each player independent of age group and their overall differing game durations (i.e., minutes), the percentage of the maximal possible game time was calculated. For example, if a player was not injured or ill but able to play and played one half time in each of the eight games the percentage is calculated as follows: maximal possible game-time percentage = 100%, actually played game-time = 50%. This maximal possible game-time percent- age was reduced to 0% when the absence reason of a player was an injury or illness, whereas the score remained at 100% if the lack was due to performance reasons.

**Injury incidences.** Injuries of the same period as game time were diagnosed by the club's medical staff and recorded if that injury prevented a player from taking a full part in all training and match-play activities typically planned for that day and prevented participation for a period greater than 24 h. This reflects the definition of Brooks et al. (2005) and conforms to the consensus definition for team sport athletes (Fuller et al., 2007). The diagnosed injuries were further classified in terms of mechanism (i.e., contact or non-contact), injury type and location which is also based on the consensus definition for team sport athletes (Fuller et al., 2007).

## Statistical analysis

Data were analyzed using IBM SPSS Statistics 26.0.0. Current recommendations to focus on estimation for best reporting and analysis practice were followed instead of conducting null-hypothesis significance tests (Cumming, 2014); effect-sizes with 95% confidence intervals are reported. Not all variables were normally distributed, as assessed by Shapiro–Wilk's test ($p < 0.05$). Therefore, Spearman's correlation coefficient test was used to investigate the correlation between the player's cognitive, physiological performance and game intelligence, game time and injuries. Correlation coefficients (Spearman's r) of 0.1, 0.3, and 0.5 represent small, moderate, and large effect size estimates, respectively (Cohen, 1988). To confirm that other factors did not confound the findings, we also performed a non-parametric partial correlation analysis (Conover, 1999), which controlled the age group.

## Results

Partial Correlations (Spearman's r) with their 95% confidence intervals and the sample sizes contributing to each correlation are stated in Tables 1, 2 and 3. Bivariate correlations and the exploratory youth- adult subgroup analysis are presented in the Appendix. A preliminary analysis (i.e., ANOVA) showed that the slightly different performance level of the U23 compared to the other teams did not influence the results substantially. Generally, results with confidence intervals not including zero are meaningful as they depict reasonable evidence of a population effect (Cumming, 2014).

**Game intelligence.** WMC, CF and the cognition score showed small to moderate correlations with game intelligence. In contrast, selective attention only showed a trend toward a meaningful correlation and inhibition showed no correlation at all. The partial correlation analysis revealed no association of age group on executive functions and game intelligence (see Table 1).

**Game time.** Moderate to large correlations with game time were present for game intelligence and CF whereby WMC, cognition score and selective attention correlated small to moderately with game time. None of the other parameters showed meaningful correlations. After controlling for the age group, the correlations with game intelligence, CF, WMC, cognition score and selective attention remained. In contrast the cor- relations with RIEA and acceleration (5 and 30 m) became meaningful on a moderate to large level as well (see Table 2). Further, the explor- atory youth-adult subgroup analysis showed small to large effect sizes for correlations with all cognitive parameters except for inhibition, and small to moderate effect sizes for correlations with both accelera- tion times in the youth group. Contrary, the adult group only showed small to moderate correlations with working memory and CF and also a moderate to large effect for inhibition.

**Injuries.**

*Contact injuries*

Only 30-m acceleration showed a small to moderate correlation with contact injuries (n = 13) whereas CF only showed a trend. None of the other parameters were meaningfully correlated. The correlation with 30-m acceleration was reversed to a negative small to moderate correlation after controlling for the age group (see Table 3).

#### *Noncontact injuries*

Small to moderate correlations with noncontact injuries (n = 22) were present for WMC, inhibition, countermovement jump and squat jump. None of these correlations remained meaningful after controlling for the age group whereas 30-m acceleration showed a moderate to large and performance-IAT showed a negative small to moderate correlation (see Table 3).

**Table 1. Partial correlations between executive functions and game intelligence whilst controlling for age group**

| | Selective Attention | Working Memory | Cognitive Flexibility | Inhibition | Cognition Score |
|---|---|---|---|---|---|
| Game intelligence | | | | | |
| Spearman's *r* | 0.16 | **0.28** | **0.30** | 0.07 | **0.29** |
| CI | -0.02, 0.33 | **0.13, 0.42** | **0.15, 0.44** | -0.09, 0.22 | **0.12, 0.45** |
| *n* | 116 | **156** | **156** | 156 | **116** |
| Included teams | U15- first-team | U13- first-team | U13- first-team | U13- first-team | U15- first-team |

**Table 2. Partial correlations between executive functions, physiological abilities and game time whilst controlling for age group**

| | Game Intelligence | Selective Attention | Working Memory | Cognitive Flexibility | Inhibition | Cognition Score | RIEA | Sprint (5M) | Sprint (30m) | Squat Jump | Counter Movement Jump | Drop Jump | Performance-IAT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Game time | | | | | | | | | | | | | |
| Spearman's *r* | **0.42** | **0.22** | **0.29** | **0.34** | -0.17 | **0.29** | **0.32** | **-0.34** | **-0.37** | -0.01 | 0.04 | 0.14 | 0.16 |
| CI | **0.25, 0.56** | **0.02, 0.40** | **0.12, 0.44** | **0.18, 0.48** | -0.33, 0.01 | **0.10, 0.46** | **0.10, 0.54** | **-0.50, -0.16** | **-0.53, -0.19** | -0.27, 0.25 | -0.14, 0.22 | -0.04, 0.31 | -0.15, 0.44 |
| *n* | **109** | **97** | **128** | **128** | 131 | **100** | **56** | **103** | **103** | 56 | 122 | 122 | 42 |
| Included teams | U13- first-team | U15- first-team | U13- first-team | U13- first-team | U13- first-team | U15- first-team | U14- U19 | U13- U23 | U13- U23 | U15- U19 | U13- first-team | U13- first-team | U16- U19 |

**Table 3. Partial correlations between executive functions, physiological abilities and injuries whilst controlling for age group**

| | Game Intelligence | Selective Attention | Working Memory | Cognitive Flexibility | Inhibition | Cognition Score | RIEA | Sprint (5M) | Sprint (30m) | Squat Jump | Counter Movement Jump | Drop Jump | Performance-IAT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Contact Injury | | | | | | | | | | | | | |
| Spearman's *r* | -0.14 | 0.04 | -0.02 | 0.12 | -0.08 | -0.04 | 0.08 | -0.08 | **-0.24** | 0.09 | 0.12 | 0.04 | -0.04 |
| CI | -0.31, 0.04 | -0.15, 0.23 | -0.18, 0.15 | -0.05, 0.30 | -0.24, 0.09 | -0.23, 0.15 | -0.18, 0.33 | -0.26, 0.10 | **-0.41, -0.06** | -0.16, 0.33 | -0.05, 0.28 | -0.13, 0.21 | -0.32, 0.25 |
| *n* | 122 | 108 | 141 | 141 | 141 | 108 | 61 | 115 | **115** | 66 | 134 | 134 | 48 |
| Noncontact Injury | | | | | | | | | | | | | |
| Spearman's *r* | 0.08 | -0.14 | 0.11 | 0.05 | 0.16 | 0.14 | -0.20 | 0.11 | **0.35** | -0.12 | -0.19 | 0.16 | **-0.29** |
| CI | -0.10, 0.25 | -0.32, 0.10 | -0.10, 0.27 | -0.12, 0.21 | -0.01, 0.32 | -0.05, 0.32 | -0.43, 0.05 | -0.07, 0.30 | **0.18, 0.50** | -0.35, 0.13 | -0.35, 0.02 | -0.01, 0.32 | **-0.53, -0.01** |
| *n* | 122 | 108 | 141 | 141 | 141 | 108 | 61 | 115 | **115** | 66 | 134 | 134 | **48** |
| Included teams | U13- first-team | U15- first-team | U13- first-team | U13- first-team | U13- first-team | U15- first-team | U14- U19 | U13- U23 | U13- U23 | U15- U19 | U13- first-team | U13- first-team | U16- U19 |

*Note.* RIEA: repeated intense exercise ability; IAT: individual anaerobic threshold; included teams: describes which teams contribute to the sample of each correlation, e.g. U13-first team indicates all teams starting from U13 up to the first team (U13,14,15,16,17,19,23, first team); boldface numbers highlighting CIs not including zero

# DISCUSSION

The identification of key characteristics of talent is a crucial facet of domains in which humans need to thrive to high-performance in complex settings. Elite soccer is one of these settings where cognitive and physio- logical abilities are essential properties of the game whereas evidence on the contribution of multidisciplinary performance data is scarce. Regarding the primary aim of the study, the present data indicate for the first time that better performance of executive functions (objective and coach-rated) is associated with an objective rating of successful soccer performance, that is, game time, across all included ages (i.e., 12–34 years). More specifically, coach-rated game intelligence and CF represent moderate to large correlations with game time and WMC, cognition score and selective attention show small to moderate correlations with game time. As only inhibition showed no meaningful correlation the first hypothesis can be partially proved. These findings are in line with previous results on the interrelation of executive functions and superior performance in elite athletes (Scharfen & Memmert, 2019a) and moderate effect sizes regarding success in soccer as measured by scored goals, assists (Vestberg et al., 2012, 2017, 2020) and the acceptance into an elite soccer academy (Sakamoto et al., 2018), which only reported small effect sizes. These previous associations of executive functions with success in elite soccer partially rely on the design fluency tests which measures higher- level executive functions planning and problem-solving (sometimes called fluid intelligence; Diamond, 2013) including creativity, response inhibition, working memory and CF (Sakamoto et al., 2018; Vestberg et al., 2017). Thus, the difference to the executive function tests used in the present study lays in the isolated measure of core executive functions compared to the combined analysis of higher-level executive functions. Although, the design fluency test has been suggested to simulate the executive decision-making chain similarly as in a real soccer situation (Vestberg et al., 2017) the core components CF and working memory have been indicated to be the main driver of the associations with success which may be confirmed by the present results. While the strength of the design fluency test is the higher eco- logically validity, the weakness which is simultaneously the strength of the isolated tests is the clear distinction which core executive functions drive a certain association. But as an important extension, this evidence might also be enlarged as the measure of success in the present study may also be even more valid since game time is commonly used (Rumbold et al., 2020) as it is achievable for players of all positions compared to goals and assists, which is more challenging to realize for defenders compared to strikers.

Similar to the correlation with game intelligence, it is remarkable that the unique relationship between executive functions and game time seems to exist across all teams as age had no meaningful effect on the correlation. Again, this could hint at a central association integral to soccer expertise at all developmental phases from age 12 up which may support both, the nature as well as the nurture hypothesis. Thus, these findings along with the relationship of game intelligence and executive functions across all age groups may be used as valuable insights into the current demands of high-performance in complex team sports like soccer as a kind of performance-needs analysis (Baker et al., 2020). More specifically, the exploratory youth-adult subgroup analysis showed that these demands may differ among youth and adult elite soccer as all cognitive and both acceleration parameters present small to moderate effect sizes in the youth group (except for inhibition) whereas only working memory, CF but contrary also inhibition were meaningfully associated with game time in the adult group. However, the fact that inhibition in the youth subgroup was not associated with game time contrasts with prior studies suggesting the importance of inhibition for soccer players with small effect sizes (Verburgh et al., 2014, 2016). Additionally, the findings enlarge the current understanding of the cognitive and physiological association with expertise and talent in certain developmental stages (Baker et al., 2019, 2020; Johnston et al., 2018; Till & Baker, 2020). Moreover, a key question is whether executive functions develop due to systematic exposure to high quantities and qualities of training (i.e., nurture) or whether this is a prerequisite to play on an elite level (i.e., nature). Recent findings of a large longitudinal study of elite soccer players question the nurture approach (Beavan et al., 2020). Although the present results are not inferential and cannot resolve that debate, they may suggest that executive functions have a substantial relation to game intelligence and game time representing essential performance parameters of the soccer game. As an important extension to previous findings and contrary to Beavan et al. (2020), these associations are already present in the youngest age group possibly hinting at a low probability that this is solely based on nurture but rather on a selection phenomenon (nature hypothesis) (Sakamoto et al., 2018) as younger children have not yet gained a long experience of soccer training. However, the difference in the applied executive function tests (e.g., no working memory or CF test in Beavan et al., 2020) and age groups (i.e., no adult elite team in Beavan et al., 2020) need to be considered which probably also contributes to the differing findings. Conversely, children in the age of 12–13 years of age playing for a professional soccer club probably have a history of several years of continual movement and motor experience which also boosts executive functions (Cox et al., 2016; Prakash et al., 2015). Thus, the nature as well as the nurture hypothesis might be supported by the present findings. Furthermore, the results of the physiological performance data show that the covariate age had a considerable effect on the interactions of the physiological parameters RIEA and sprint with game time which could be explained by the fact that younger players' physiological capabilities are less developed compared to older players resulting in slower sprint times and lower endurance performance. By eliminating this age effect through partial correlation analysis, the underlying substantial association became noticeable. More specifically, the abilities RIEA and sprint (5 and 30-m time) were correlated on a moderate level with game time, confirming similar results of moderate effects of a previous review (Murr, Raabe, & Höner, 2018) concerning their relation to success (i.e., the entrance to the next development stage of an elite youth academy). Thus, the first hypothesis can only be partially confirmed. This association seems intuitive as these skills are constantly mentioned as important performance indicators in soccer (Oone et al., 2012; Reilly et al., 2000). However, small differences between the current RIEA and endurance tests included in the review cannot be excluded and should therefore be considered. None of the other physiological parameters showed meaningful associations and only negligibly effect sizes—except for drop jump and performance-IAT trends showing small effect sizes, which is contrary to moderate effect sizes of prior review evidence (Murr, Raabe, & Höner, 2018) and our hypothesis. Consequently, the present results suggest that mainly the executive functions (except for inhibition) along with the physiological abilities sprint and RIEA (only in the youth subgroup) contribute meaningfully to the game time of elite soccer players. As an essential addition, the current findings may partially answer the question of Beavan et al. (2020) in terms of the association of domain-generic executive functions and success in elite soccer. However, the smaller sample sizes of the physiological parameters RIEA, squat jump and performance-IAT compared to the cognitive parameters also need to be considered. The secondary aim of this study was to analyze the extent to which the multidisciplinary performance data are associated with injuries. Concerning contact injuries, only the 30-m sprint represents a meaningful negative correlation with contact injuries (i.e., small to moderate). The covariate age influenced this correlation (i.e., switching substantially from positive to negative), which may again be explained by the fact that the youngest teams (i.e., U13-U15) are slower than their older peers based on their developmental phase. As players of this age group sustained no injury at all,

this incidence distorted the primary bivariate correlation before controlling for age. However, this counterintuitive result proposing that physically faster players sustain more contact injuries is not in agreement with previous literature suggesting that better sprint performance reduces the injury risk (Malone et al., 2018) in adult elite soccer players and contradicts our fourth hypothesis. Yet, it is unclear whether the relation- ship of the study (Malone et al., 2018) mentioned above is evident in all types of injuries (i.e., contact vs. non-contact). One could argue that faster players could have more duels and therefore contacts with other players resulting in an increased probability to sustain an injury. As 92% of the contact injuries are related to the lower limbs (see Appendix 6), this might indicate that the possible higher velocities of faster players may intensify the impact of those duel-contacts with opposing players and therefore increase the injury risk. Additionally, the higher mechanical load in faster players could also contribute to this heightened risk (Beato & Drust, 2020). Nevertheless, this is somewhat speculative as this association is the first of its kind to our knowledge. It also needs to be considered that no con- tact injuries occurred in the age groups U13-U15. Moreover, although previous literature suggests that executive
functions are related to injuries with moderate to large effect sizes (Swanik et al., 2007) and injury-risks (Giesche et al., 2020; Monfort et al., 2019), no meaningful correlation with contact- and non-contact injuries were observed in the present study, contrary to our second hypothesis. However, the different study designs of the previous investigations, including amateur athletes of various sports with predominantly controlled injury testing situations, may also explain this discrepancy. The current study analyzed the relationship between multidisciplinary performance data and elite athletes' injuries for the first time. Regarding the second injury classification, “non-contact,” a moderate to large correlation of sprint (30-m) was present, indicating a lower non-contact injury incidence in faster players. This confirms previous studies indicating a lower injury risk in athletes with higher speed (Malone et al., 2018, 2019) and partially our hypothesis. 50% of all non-contact injuries (see Appendix 6) are related to musculature, which is in line with previous studies suggesting that well-developed sprinting-related muscles reduce the injury risk (Malone et al., 2018, 2019). However, as a crucial expansion, present findings also show that the player's developmental phase influences this relationship. Lastly, performance-IAT was negatively and small to moderately correlated with non-contact injuries suggesting that players with better anaerobic endurance performance are less likely to sustain a non- contact injury. Fatigue results in a higher injury

risk based on lower coordination performance, among other factors due to decreased neuromuscular control (Huygaerts et al., 2020). Thus, as players with a better performance at the IAT get fatigued later, their injury risk may be reduced. Further, this association is also in line with the protective function of a well-developed cardiovascular and musculoskeletal system (Gabbett, 2016). Again, the covariate age had a meaningful effect on both associations, similar to the contact injuries. However, the smaller sample size and the fact that the performance-IAT parameter was only present for the teams U16-U19 need to be considered. The third, exploratory hypothesis of study can be confirmed by the present results for the most part and propose that coach-rated game intelligence correlates small to moderately with the executive functions working memory and CF. In contrast, selective attention and inhibition had no relation with game intelligence. In agreement with the current investigation, a previous study (Vestberg et al., 2020) found a moderate correlation of coach-rated game intelligence with design fluency, a test combining all three executive functions. The correlation of that study was slightly smaller than that of the present investigation (r = 0.37; 0.42, respectively) which could be based on the sample size twice as large in the current study. Even more importantly, for the first time, the present study not only shows this relationship in adults but also in adolescents and children. Specifically, the current association seems to be present across all developmental stages (i.e., all tested age groups) as age had no meaningful effect on the correlation. This might significantly expand the findings of adult players and point at a fundamental linkage inherent to the soccer expertise at all included phases of age. Further, it was proposed that specifically CF may contribute to game intelligence, which can be confirmed based on the present findings. Contrary to the current results, no correlation between game intelligence and working memory was found in the aforementioned study (Vestberg et al., 2020). This could be based on the difference in the applied working memory test which was a one-back working memory test with a subversion including a variable n-back in which the subject has to respond if he or she has seen a displayed card any time earlier in the test sequences. Although, these n-back versions are valid tests they may not depict the ecologically valid demands of the dynamic and complex soccer game on the working memory system. On the other hand, the counting span working memory task applied in the present study required the participant to count randomly arranged, specific shapes among distractors and afterward remembering the count totals for later recall. After the presentation of 2–7 images a recall mask occurred into which the participant had to fill their memorized count totals in the exact order they had been illustrated in. However, when also considering the superiority of working memory in elite soccer players evident in previous studies (Vestberg et al., 2012, 2017), the results altogether suggest an importance of working memory for successful soccer behavior in youth as well as adult players. Thus, especially CF and WMC seem to be associated with game intelligence. Limitations of the current study should also be acknowledged. Although multidisciplinary performance data were used, it still does not capture the complexity of a team sport like soccer holistically as technical/tactical skills and psychological abilities (e.g., resilience) are missing which have been reported as important properties (Formenti et al., 2020; Gabbett et al., 2007). Additionally, while current research indicates that the included performance parameters are important properties of elite soccer, it is still possible that other parameters which were not analyzed may also contribute essentially to success in elite soccer. Lastly, due to the partially differing sample sizes contributing to the individual parameters (i.e., RIEA, IAT, SJ) these associations, of course, have a smaller precision and power to detect effects if they exist compared to those with a larger sample size >100. Specifically, the precision of the confidence interval and the likelihood of the correlation of game time with working memory and CF (n = 128) revealing the actual and representative value is much higher than the precision of the correlation of performance-IAT with game time (n = 42). Thus, the interpretation of the correlations with the three parameters RIEA, performance-IAT and SJ could be a little biased compared to all other parameters which include a sample size of more than 100 players. Consequently, this potentially skewed demonstration of the actual population value always needs to be considered in the interpretation of the present findings. Thus, it should not be inferred that the effect of cognitive functions on game time is generally larger than the effect of the performance-IAT but rather that the likelihood of this larger effect is just bigger based on the larger sample size. Taken together, one should interpret the findings with different evidence levels. Specifically, the parameters with a sample size of >100 and <100 may represent evidence levels A and B, respectively. How- ever, future research needs to confirm this likelihood in studies with equal sample sizes for both parameters. This also leads to differing injury numbers as not all parameters are present for each team resulting in not considering injuries of that specific team where no data are available (e.g., for IAT). Furthermore, no control group of fit- ness and age matched or female athletes were included which could be be an important aspect of future research. In total, the age-independent and fundamental associations of executive functions with game intelligence and game time may extend previous findings and their importance for elite soccer expertise at all ages besides providing insights into current demands of high- performance in complex team sports like soccer as a performance- needs analysis (Baker et al., 2019). Thus, future research should further research possibilities to enhance these executive functions as current training tools seem to evoke very limited transfer (Scharfen & Memmert, 2021). Further, the applied, unique multidisciplinary approach also highlights the crucial role of specific physiological abilities for success in soccer regarding game time and age-dependent injury avoidance. Future studies should also include technical/ tactical as well as psychological (i.e., resilience) skills to create a holistic approach to talent identification and the endeavor to track their future success. Moreover, more sophisticated parameters are needed to capture the multifaceted construct of success in a dynamic and complex setting like elite soccer (Memmert & Raabe, 2018).

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## Appendix V: Publication V

# Cognitive training in elite soccer players: evidence of narrow, but not broad transfer to visual and executive functions

**Reference:**
Scharfen, H. E., & Memmert, D. (2021). Cognitive training in elite soccer players: evidence of narrow, but not broad transfer to visual and executive function. *German Journal of Exercise and Sport Research*, *51*(2), 135–145.

# ABSTRACT

Visual and executive functions have been suggested to be one of the crucial factors in high-demanding team sports. Consequently, the interest in evaluating training possibilities of these functions is relatively high. However, easily applicable training tools, as well as evidence of their efficacy, especially in the present group of age (i.e. 17-21) and performance level, are scarce. Therefore, the present study aimed to evaluate the effectiveness and transfer of an essential cognitive training tool (i.e. NeuroTracker (NT) 3 dimensional (3D) multiple-object tracking (MOT) in youth elite soccer players. Visual and executive functions were analyzed in a pre-post-test design with an intervention and a control group after 10 weeks of training twice a week. Physical activity was included as a possible covariate. Results show meaningful benefits in the trained ability (i.e. MOT) besides small but negligible improvements in visual clarity and inhibition for the intervention group. Consequently, strict single-task NT 3D-MOT seems to have little transfer to other visual or executive functions. However, future studies should especially investigate the effects of sport-specific dual-task NT 3D-MOT to analyze possible multitasking adaptations further.

*Keywords*: perceptual functions, multiple-object tracking, high-performance athletes,
brain training

## INTRODUCTION

Athlete’s advantages in visual and cognitive functions cause increasing interest and attention in practitioners and scientists across the domains of sport psychology, sport science and cognitive neuroscience (Huang, Davis, Wolff & Northoff, 2017; Callan & Naito, 2014; for review see, e.g. Yarrow, Brown & Krakauer, 2009). One way to analyze this advantage is called the expert-performance approach, which investigates the athlete’s visual and cognitive expertise employing sport-specific stimuli in sport-specific contexts (e.g. decision-making in sport-specific settings, domain-specific). Studies of this approach showed faster and more accurate performance of elite- compared to amateur or semi-elite athletes (for a meta-analysis see Mann, Williams, Ward & Janelle, 2007). Additionally, more recent studies belonging to a second category called cognitive component skill approach investigate fundamental visual and cognitive skills in sport-unspecific contexts (i.e. domain-general). Results of these studies indicate a superiority of elite- compared to amateur or semi-elite athletes in fundamental processes (for a meta-analysis see Voss, Kramer, Basak, Prakash & Roberts, 2010; Scharfen & Memmert, 2019). This domain-general cognitive superiority is best documented in elite soccer players in terms of executive functions (Vestberg, Gustafson, Maurex, Ingvar & Petrovic 2012; Vestberg, Reinebo, Maurex, Ingvar, & Petrovic, 2017; Verburgh, Scherder, van Lange & Oosterlaan, 2014; 2016; Huijgen, Leemhuis, Kok, Verburgh, Oosterlaan, Elferink-Gemser, & Visscher, 2015). These executive functions include the cognitive processes that regulate thoughts and actions, especially in non-routine situations (Miyake & Friedman, 2012). Additionally, they are further subdivided into core executive functions, which include working memory, cognitive flexibility and inhibitory control, and higher-level executive functions, involving reasoning, problem-solving and planning (Diamond, 2013). These higher-level functions altogether are also called metacognition (Vestberg et al., 2012).

Moreover, athletes with sophisticated domain-general visual functions like visual clarity and depth perception seem to have a higher success rate in team sports (Burris, Liu & Appelbaum, 2019; Roberts, Strudwick & Bennett, 2017). Although domain-general visual and executive functions are deeply linked to each other, their dissociation is quite essential in this case. The core area of vision provides sensory information of the outside world and depends on afferences (i.e. input streaming to the brain) for the most part. In contrast, executive functions are also linked to the processing of that sensory information (Gilbert & Burgess, 2008).

Another line of evidence regarding these functions indicates that physical activity is a crucial booster for cognitive processes by triggering processes like enhanced cerebrovasculation and the release of neurotropic factors like BDNF (brain-derived neurotrophic factor; for review see Prakash, Voss, Erickson & Kramer, 2015; Cox, O'Dwyer, Cook, Vetter, Cheng, Rooney, O'Connor, 2016). The combination of this physical boosting with the cognitive superiority of elite soccer players leads to the conclusion that extensive soccer practice might result in an implicit training of these functions. However, the mainly cross-sectional nature of this evidence does not allow causal conclusions.

Based on the superiority of elite athletes in terms of visual and executive functions, the interest to evaluate training possibilities of these skills is very high. One example of these training possibilities belongs to the cognitive component skill approach which targets fundamental subprocesses (for review see Appelbaum & Erickson, 2018; Hadlow, Panchuk, Mann, Portus & Abernethy, 2018). A widely applied training-program associated with this approach is called NeuroTracker (NT) 3 dimensional (3D) multiple-object tracking (MOT) (Faubert, 2013).

First longitudinal studies using this NT 3D-MOT to train young athletes showed heterogeneous results. One of these studies was conducted by Parsons and colleagues (2016), who examined university students after five weeks of training by using a quantitative electroencephalogram and a battery of neuropsychological tests. They found enhanced attention, visual information processing speed, working memory and a higher amount of allocatable neural resources. However, the applied working memory test is questionable as the required cognitive functions are related to short-term memory for the most part, whereas the other tests are valid. In another study, Fleddermann et al. (2019) compared cognitive and sport-specific adaptions of elite volleyball athletes after 8 weeks of training with those of an active control group. More specifically, processing speed, memory span, working speed, sustained attention, and a volleyball-specific test were analyzed through several neuropsychological tests. Significant improvements were found in processing speed and sustained attention. However, these results need to be interpreted with caution as sport-specific motor actions were part of the NT 3D-MOT training as well. Romeas et al. (2016) showed improved passing decision-making accuracy in amateur soccer players after five weeks of training. They analyzed small-sided soccer games in a pre-post design with an active and a passive control group. Contrary to those results, Moen, Hrozanova and Stiles (2018) found no significant improvements in executive functions in elite athletes from dynamic sports after five weeks of training. However, those results need to be interpreted with caution as the number of absolved sessions in this study was highly differing.

Furthermore, one core principle of the NT 3D-MOT used in the previous studies is the adaptability of task difficulty. Concerning this principle, two opposed theories have been proposed to explain individual differences in training-related performance gains (for review see Karbach & Unger, 2014). First, the magnification account suggests that individuals who already perform on a high level will benefit most from cognitive training. According to this theory, high-performing individuals have more cognitive capacities to acquire new skills. Second, the compensation theory assumes that low-performing individuals will benefit more from cognitive training as their room for improvement may be relatively large (Karbach & Unger, 2014).

By reviewing the current literature on NT 3D-MOT training in young athletes, it is conspicuous that only basic cognitive mechanisms like processing speed are improved. In contrast, higher cognitive processes as executive functions are not enhanced by training except for attention. Furthermore, none of the few studies investigated the covariate physical activity which is a crucial booster for cognitive functions (Prakash et al., 2015; Cox et al., 2016). Therefore, the depicted improvements after NT 3D-MOT training could be inaccurate due to this influence. Further, it is unclear whether the few improvements in fundamental cognitive processes are originated in this area or whether this is based on adapted processing of visual skills. This uncertainty is based on the so-called transfer phenomenon which entails the two opposing theories of narrow and broad transfer (Furley & Memmert, 2011). These theories were further categorized by Zentgraf, Heppe & Fleddermann (2017) into task-specific (i.e. improvements in the trained task), near (i.e. similar cognitive task), further (i.e. other not related cognitive tasks) and far (i.e. transfer to competition). In the present investigation task-specific, near- and further transfer effects are examined. The study with the largest further-transfer results used a sample of university students (Parsons et al., 2016). Learning curves have been shown to differ substantially among elite athletes and university students (Faubert, 2013). This suggests that a simple transfer from changes in students to changes in elite athletes is not suitable and should be interpreted with caution when seeking to apply such findings to world-class elite athletes directly. Consequently, it is not sure that the improvements are not merely an effect of those physical exercises. Furthermore, three of the four studies investigated effects after five training weeks which is a relatively short time. Therefore, it might only depict a very limited snapshot of possible training effects.

Due to this substantial methodological heterogeneity in recent literature, an analysis from a fundamental standpoint showed that the expected involvement of visual and executive functions in the NT 3D-MOT is relatively low (see Appendix 2). This expectation is based on the requirements of the task, which are very specific and don't contain other visual or cognitive elements besides the MOT skill. Contrary, several claims are made that the NT 3D-MOT enhances executive- and some visual functions like the visual field, depth perception and attention (Faubert & Sidebottom, 2012, Parsons et al., 2016). The mismatch of these claims is accompanied by the low theoretical probability of fulfilling them. When also taking the heterogenous literature on NT 3D-MOT transfer into consideration a fundamental examination of this tool seems essential in order to rigorously evaluate its practical importance (Walton, Keegan, Martin & Hallock, 2018).

In order to clarify the recent literature gaps and by following current recommendations (Harris et al., 2018; Walton et al., 2018), the present investigation is unique in several key aspects. Namely, the aim was to analyze the transfer effects of training intervention with the NT 3D-MOT on both visual and executive functions in a pre-post-test design with a training- and a control group. Accordingly, the training intervention was conducted with a strict single-task NT 3D-MOT in elite soccer players between 17 and 21 years of age over 10 weeks. The applied visual tests are used for measures of the transfer due to their fundamental role in the process of perception (Burris, Liu & Appelbaum, 2019; Hüttermann, Memmert & Simons, 2014). The executive function tests are included based on their apparent importance in elite soccer (e.g., Vestberg et al., 2012; 2017; Verburgh et al., 2014; 2016; Huijgen et al., 2015). Additionally, the covariate physical activity was included to analyze possible influences on the outcome measures. Moreover, the prediction of NT 3D-MOT performance gains using pre-test performance was analyzed as well. Specifically, the opposing magnification- and compensation theories were examined, proposing an amplification of higher- or compensation of lower baseline performance, respectively.

## Methods

### Participants

A total of 29 elite soccer players from the talent development program of the youth academy of a professional German soccer club were recruited. They were further divided into a training- (n = 16) and a passive control group (n = 13) by their coaches. The participants were males born between 1997 and 2003 ($M_{age}$= 18.77 years, $SD_{age}$= 1.42). At the time of data collection, their teams were playing at the top level of their respective age group (U19 team) or the fourth-highest senior league (U23 team). Participants did not report any behavioral, learning, or medical condition that might influence cognitive abilities. Their physical fitness and educational level was homogenous and written informed consent was obtained from every participant before commencing the experiment. The study was carried out in accordance with the Helsinki Declaration of 1975 and was approved by the ethics committee of the German Sport University Cologne.

#### Measures.

##### *Visual Tests.*

The *NT 3D-MOT* task with the NeuroTracker™ Core Program by CogniSens Athletics Inc. from the University of Montreal was used for the training intervention as well for one pre- and posttest. This task was used as a manipulation analysis to ensure that a possible lack of transfer is not based on a lack of improvement in the trained task. The program was depicted on a wall via a video projector. NT 3D-MOT settings were the same as in Faubert (2013). During the session, eight yellow balls were presented, of which four changed their color for 1 s to orange. Participants were asked to memorize these balls. Then, that all balls moved randomly through the 3D domain with a specific velocity for 8 s. After 8 s, the spheres stopped moving, and the participants were asked to indicate the four “orange” balls (targets). Afterwards, participants got feedback, and the next trial started. One session lasted about 8 minutes and consisted of 20 trials. The dependent measure was the average speed threshold among all trials (for detailed information see Faubert, 2013).

*Attention window* was assessed with the Attention Window task by Hüttermann et al. (2014). The individual attention breadth on diagonal, horizontal and vertical axis was measured. During each trial, participants were instructed to fixate a central point and try to spot a white triangle within a circle (1.1° diameters) among square distractors (1.1° × 1.1°). Across trials, the target appeared at varying distances from the fixation point (10°, 20°, and 30°) along with one of eight equally spaced radial lines that originated from a square in the center of the display (45° apart). This random display was flashed for 12 ms and followed by a colorful mask (100 ms). After every mask, subjects were asked to indicate how many white triangles they had just seen in the different locations depending on the orientation of the items. Participants completed 144 trials. This particular task measures how well people can attend to objects appearing far from fixation. The high quality of the testing criteria has been described in a recent review (Hüttermann & Memmert, 2017). The assessment lasted about 12 minutes, and the dependent measure was the accumulated value of all three dimensions (diagonal, horizontal, vertical) divided by the number of the measurements (i.e., three) in degree (Scharfen & Memmert, 2019b).

The Senaptec Sensory Station was used to assess a variety of visual skills (i.e. *visual clarity, contrast sensitivity, depth perception, near-far quickness, target capture, perception span, multiple-object tracking, reaction time*) with proven reliability (for a detailed description of the procedure and reliability see Erickson et al. 2011). The assessment lasted about 20 minutes. Dependent measures of the individual visual functions are described below.

*Visual clarity*: ability to process non-moving visual information while standing still. Dependent variable: threshold of the static visual acuity (depending on individual adapting staircase algorithm)

*Contrast sensitivity*: ability to process spatial or temporal information about objects and their backgrounds under varying lighting conditions. Dependent variable: threshold sensitivity (depending on individual adapting staircase algorithm)

*Depth perception*: determining distance and spatial localization of an object. Dependent variable: threshold depth perception (depending on individual adapting staircase algorithm)

*Near-far quickness:* ability to quickly switch the gaze between far, intermediate, and near distances requiring rapid accommodative-vergence responses. Dependent variable: number of correct responses

*Target capture*: ability to process moving visual information while standing still. Dependent variable: threshold stimulus exposure (depending on individual adapting staircase algorithm)

*Perception span*: speed and span of recognition of tachistoscopic information. Dependent variable: cumulative number of correct responses

*Reaction time*: reacting as fast as possible to occurring visual stimuli by touching them. Dependent variable: elapsed time between onset and touching of the test stimuli

### *Executive Function Tests.*

### *Core Executive Function Tests*

*Working Memory Capacity* was measured by using the well-established working memory span test by Conway, Kane, Bunting, Hambrick, Wilhelm & Engle (2005). It measures the athlete's ability to direct attention toward the current task without getting distracted by other thoughts. More specifically, we used a counting span task (see Kane, Hambrick, Tuholski, S.W, Wilhelm, Payne & Engle, 2004 for a detailed description), as the simplicity of this processing task makes it usable for almost any type of participant (Conway et al., 2005). The instructions were presented as a written text on the computer screen. The counting span task involved counting specific shapes among distractors and then remembering the count totals for later recall. Each stimulus display contained randomly arranged dark blue circles, green circles, and dark blue squares. The task of the participants was to count aloud the dark blue circles and then name the total count aloud at the end. A recall mask occurred after 2–6 stimulus displays into which participants had to fill their memorized count totals in the exact order they had been displayed in. The participants counting span score was a partial credit load score (cf. Conway et al., 2005) which represents the sum of all correctly identified elements – whereby a correctly recalled item from a set containing two items receives 2 points, and a correctly recalled item from a set with 6 items receives 6 points – divided by the maximum possible score. Good reliability and validity for this test have been reported elsewhere (see Conway et al., 2005). The test consisted of 15 trials, and the assessment lasted about 13 minutes. The dependent measure was the score of correctly memorized objects in percentage from a maximum of 100 (Scharfen & Memmert, 2019b).

*Cognitive Flexibility* was measured with the Trail Making Test (TMT) which consisted of two parts (A and B) (Sánchez-Cubillo, Periáñez, Adrover-Roig, Rodríguez-Sánchez Ríos-Lago, Tirapu & Barceló, 2009). The TMT-A is regularly applied to assess visuoperceptual abilities, whereas

TMT-B is used to assess cognitive flexibility (Crowe, 1998). A smaller B-A difference suggests better cognitive flexibility (for detailed a description see Huijgen et al., 2015). A validated tablet version of the TMT was used which is congruent with the traditional pen-paper version that has been shown to be reliable and valid (Sánchez-Cubillo et al., 2009; Delbaere & Lord, 2015). The assessment lasted about 5 minutes, and the dependent measure was the B-A difference in seconds.

*Inhibition* was measured with a Go-NoGo task which was also included in the Senaptec Sensory Station test battery. Yellow-green dots required the athlete to touch them as fast as possible (i.e. Go condition) whereas red dots should not be touched (i.e. No-Go condition). Ninety-six total dots (64 yellow-green, 32 red) were presented in a pseudorandomized sequence to maintain equivalent spatial distribution. The assessment lasted about 3 minutes, and the dependent measure was the cumulative value of touched Go stimuli minus any NoGo stimuli touched (for a detailed description see Erickson et al., 2011).

*Higher-level Executive Function Test*

*Metacognition* was measured with the standardized Design Fluency test, which assesses online multi-processing such as creativity, response inhibition, and cognitive flexibility (Homack, Lee & Riccio, 2005; Swanson, 2005). This test belongs to the Delis-Kaplan system and assesses performance relying on both core- and higher-level executive functions, thus stimulating the executive chain of decision-making. The task requires connecting dots with four lines under time pressure (60 sec) to produce as many different patterns as possible. The participant is not allowed to use the same solution twice. A computerized version of this test with good reliability was used. The assessment lasted about 5 minutes (i.e. 4 rounds of 60 sec), and the dependent measure was the number of unique created patterns (for a detailed description see Woods, Wyma, Herron & Yund, 2016).

**Procedure.**

Visual and executive function test data were collected in a separate and quiet room. The test session consisted of one session lasting approximately 75 minutes and was conducted before a soccer training. A battery of six tasks described above was used to explore individual differences in visual and executive functions. The order of the tests was fixed for all participants, which is a standard method in neuropsychological assessment, especially with small samples: 1) NT 3D-MOT, 2) Attention Window, 3) Working Memory Capacity, 4) Metacognition, 5) Cognitive Flexibility, 6) Visual Functions and 7) Inhibition. In the assessments 1, 2, 3, 4 and 5 all participants were instructed to sit in a comfortable position leaning against the backrest of the chair so that the distance to the screen was the same for all the players. Further, a computer screen was used for all these assessments (i.e. 1-5) except for 1) in which the program was depicted on a wall via a video projector. Test 6) was conducted by utilizing the Senaptec Sensory Station with the player standing in front of it (for a detailed description of the procedure see Erickson, Citek, Cove, Wilczek, Linster, Bjarnason, & Langemo, 2011). The NT 3D-MOT was used for the training intervention in the training group besides their regular team practice, whereas the control group continued their regular team practice without any additional tasks. One experimenter tested all players in a standardized process. Data on physical activity included the training duration per week per player as daily documented by the coaches of the individual teams, in which only the team training activities were considered. These data were further combined with the leisure time activity collected through a questionnaire (i.e. asking the player to state their average leisure time activity in hours per week including all physical activity besides the regular training program of the youth academy).

### ***Training intervention.***

The *NT 3D-MOT* task (described above, see also Appendix 2) was used for the training intervention. The training group (*n*= 16; $M_{\text{age}}$= 18.87 years; *SD*= 0.89) actively practiced 20 times; twice a week for 10 weeks in addition to the regular ball and athletic training. During each practice, they participated in three CORE sessions of NT, 3D-MOT (Romeas et al., 2016). Every participant reached a total of 60 sessions at the end of the training phase. They followed the same standard procedure and completed the first five practices seated and the following fifteen practices standing (i.e. 15 and 45 sessions; respectively). For a more detailed description of the NT 3D-MOT see Romeas et al. (2016). The control group (*n*= 13; $M_{\text{age}}$= 18.64 years; *SD*= 1.94) progressed with their regular practice, such as ball and athletic practice. Physical activity (i.e. training time and physical activity in leisure activity) was controlled for in both groups as it has been shown to improve cognitive performance (Prakash, et al., 2015; Cox et al., 2016)

### *Statistical analysis.*

Data were analyzed using IBM SPSS Statistics 26.0.0. Instead of conducting null-hypothesis significance tests, we followed recent recommendations to focus on estimation for best reporting and analysis practice (Cumming, 2012, 2014); we report effect-sizes with 95% confidence intervals which have also been conducted successfully elsewhere (e.g., see Kreitz, Furley, Memmert & Simons, 2014; Ivarsson, Andersen, Johnson & Linwall, 2013). Effect sizes (cohen's *d*) of 0.2, 0.5, and 0.8 represent small, medium and large effect size estimates (Cohen, 1998). Visual inference in conjunction to the analysis of proportion overlap was conducted in order to compare the mean performance change of both groups directly (i.e., the smaller the overlap of the confidence intervals the larger the meaningful difference). This procedure has been proposed as the best reporting practice (Cumming & Finch, 2005). With regard to testing predictive ability of pretest performance on NT 3D-MOT performance gains and to analyze the two opposed theories, we examined the correlation of pretest performance (i.e. executive and visual functions) and performance gains in the NT 3D-MOT. Previously, NT 3D-MOT performance gains were calculated by analyzing the difference from pre- to posttest performance using Excel (2016). Shapiro-Wilk test was used for testing for normal distributions. Not all variables were normally distributed, as assessed by Shapiro-Wilk's test ($p < 0.05$). Therefore, the Spearman's correlation coefficient test was used to investigate the correlation between the player's pretest performance and performance gains in the NT 3D-MOT.

## Results

Descriptive statistics, as well as confidence intervals and effect sizes of pre- and post-tests of both groups' visual and executive functions are depicted in Table 1. The intra-group performance differences (i.e. among pre- and post-test of the individual groups) in the NT 3D-MOT are presented in Figure 1. The intra-intervention group effect size difference of performance change in NT 3D-MOT, MOT, and inhibition was more extensive (i.e. medium to large) than the effect size difference of performance change in the control group (i.e. large, negligible and small). Contrary, the intra-group performance differences for near-far quickness was larger in the control group than in the intervention group. However, the proportion overlap (i.e. small or not existent indicating meaningful difference, Cumming &

Finch, 2005) of the inter-group effect size difference of performance change (i.e. pre-post changes from the intervention- compared to the control group) was only meaningful in the NT 3D-MOT- and MOT score as depicted in Figure 2.

Confidence intervals and effect sizes of the results showed medium to large intra-intervention group improvements in the performance of NT 3D-MOT, working memory, cognitive flexibility, inhibition, metacognition, MOT, attention window and processing speed (i.e. reaction time) besides a large effect size in near-far-quickness performance in the control group. All other parameters demonstrate no- or only small changes which could also be based on random fluctuations.

Table 1. *Mean results of all tests (pre- and posttests) for both groups.* [a] *= lower score indicating better performance; ES = effect size (d) Note: the group's performance level in the pretest did not differ substantially except for visual clarity. All scores are further described in the method section*

| | Intervention Group | | | | | | Control Group | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pretest | | Posttest | | Change (CI 95%) | ES | Pretest | | Posttest | | Change (CI 95%) | ES |
| | *M* | SD | *M* | SD | | | *M* | SD | *M* | SD | | |
| NeuroTracker speed threshold | 1.45 | 0.57 | 2.53 | 0.41 | 1.08 (0.81 to 1.38) | 2.2 (1.3, 3) | 1.18 | 0.37 | 1.61 | 0.49 | 0.43 (0.19 to 0.65) | 0.99 (0.2, 1.7) |
| Attention Window in degree | 11.38 | 6.24 | 19.22 | 6.57 | 7.79 (3.87 to 11.70) | 1.22 (0.5, 2) | 12.36 | 6.22 | 18.7 | 6.82 | 6.33 (3.76 to 8.91) | 0.96 (0.2, 1.8) |
| Working Memory score in % | 71.06 | 10.34 | 79.6 | 8.42 | 8.52 (5.85 to 11.21) | 0.91 (0.2, 1.5) | 65.38 | 10.32 | 73.69 | 10.33 | 8.31 (2.99 to 13.63) | 0.81 (0.1, 1.5) |
| Metacognition score | 12.9 | 1.66 | 15 | 1.88 | 2.10 (0.87 to 3.32) | 1.17 (0.3, 1.8) | 13.19 | 1.62 | 14.57 | 1.66 | 1.37 (0.26 to 2.51) | 0.83 (0, 1.5) |
| Cognitive Flexibility in s[a] | 28.56 | 8.59 | 21.00 | 8.40 | -8.57 (-12.04 to -5.07) | 0.89 (0.2, 1.5) | 29.97 | 10.31 | 19.60 | 9.07 | -9.11 (-13.40 to -4.73) | 1.07 (0.2, 1.9) |
| Visual Clarity score | 12.37 | 96.63 | 38.07 | 137.41 | 25.63 (-26.67 to 77.87) | 0.22 (-0.5, 0.8) | 86.62 | 65.86 | 74.78 | 61.91 | -11.82 (-55.67 to 32) | -0.19 (-1, 0.6) |
| Contrast Sensitivity score | 1.90 | 0.18 | 1.90 | 0.17 | 0 (-1.0 to 1.0) | 0 (-0.7, 0.7) | 1.92 | 0.13 | 1.74 | 0.46 | -0.17 (-0.43 to 0.07) | -0.52 (-1.3, 0.3) |
| Depth Perception score | 189.81 | 79.97 | 193.43 | 73.00 | 4.31 (-28.84 to 37.47) | 0.05 (-0.5, 0.6) | 170.31 | 89.19 | 159.13 | 83.25 | -11.18 (-52.44 to 30.08) | -0.13 (-0.9, 0.5) |
| Near-Far Quickness score | 28.20 | 7.13 | 31.27 | 7.43 | 3.07 (-0.27 to 6.42) | 0.41 (-0.3, 1) | 24.15 | 6.87 | 31.38 | 4.68 | 7.22 (3.17 to 11.28) | 1.23 (0.4, 2.1) |
| Target Capture score[a] | 176.67 | 46.74 | 190.00 | 58.09 | 18.75 (-51.91 to 14.41) | 0.24 (-1, 0.3) | 203.85 | 70.60 | 223.08 | 89.83 | 19.22 (-46.92 to 8.46) | 0.24 (-1, 0.4) |
| Perception Span score | 48.38 | 9.41 | 49.63 | 9.22 | 0.92 (-1.86 to 3.74) | 0.12 (-0.6, 0.7) | 41.31 | 9.91 | 46.23 | 12.34 | 4.91 (-0.31 to 10.16) | 0.44 (-0.3, 1.2) |
| Multiple Object Tracking score | 2107.69 | 862.48 | 2570.36 | 559.64 | 462.68 (148.53 to 776.81) | 0.64 (-0.1, 1.2) | 1853.41 | 691.27 | 1791.39 | 491.49 | -62.01(-295.70 to 171.68) | -0.13 (-0.9, 0.7) |
| Inhibition score | 9.87 | 5.54 | 14.00 | 4.74 | 4.12 (1.95 to 6.32) | 0.8 (0.1, 1.4) | 12.00 | 5.28 | 12.92 | 4.65 | 0.91 (-1.74 to 3.60) | 0.19 (-0.6, 1) |
| Reaction time in ms[a] | 300.60 | 27.59 | 284.20 | 20.33 | -16.4 (-26.36 to -6.44) | 0.6 (0.1, 1.4) | 301.62 | 22.05 | 286.31 | 14.65 | -15.31 (-23.22 to -7.40) | 0.82 (0, 1.5) |

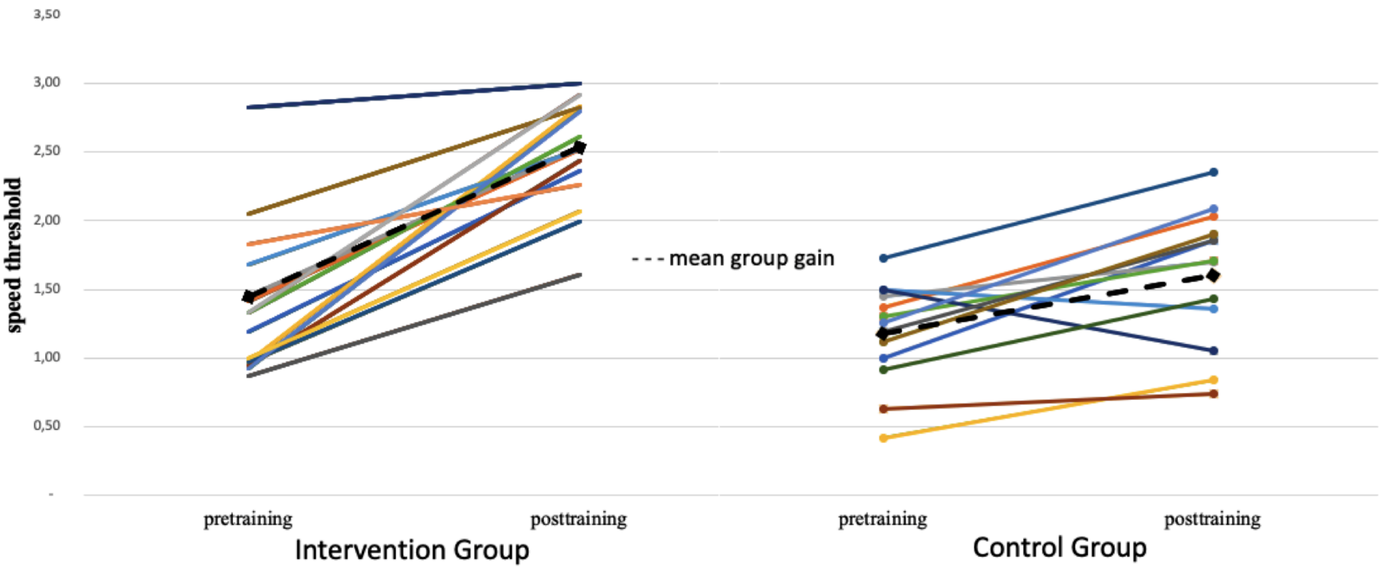

*Figure 1.* Mean speed thresholds of the NT 3D-MOT of all athletes are represented in continuous lines whereas dashed lines represent mean speed threshold gains.

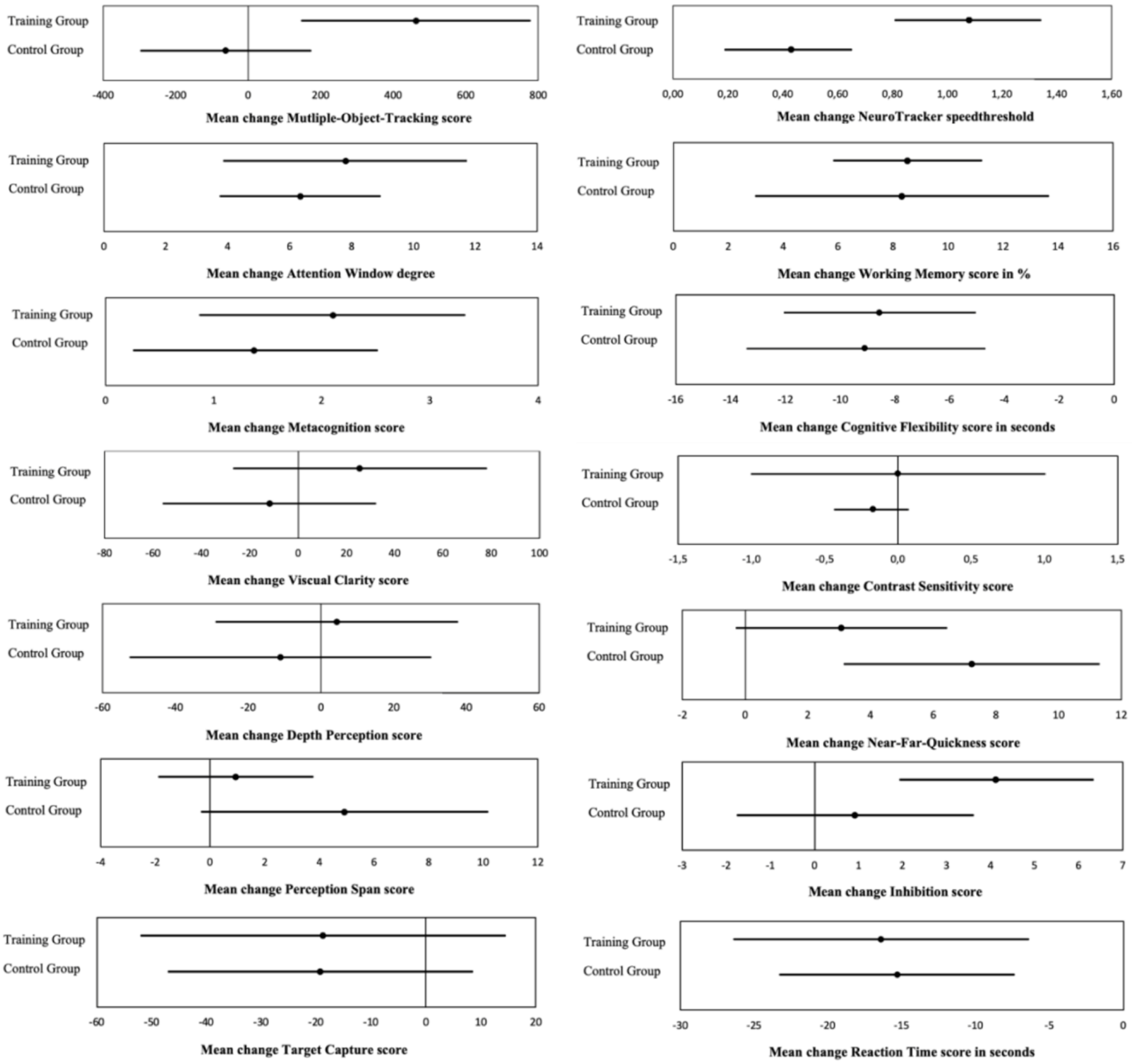

*Figure 2.* Mean performance changes with 95% CI of all tests for both groups.

***Prediction of NT 3D-MOT performance gains.***

NT 3D-MOT performance was strongly negatively correlated with NT 3D-MOT performance gains [$r_S$ (16) = - 0.851 (CI: -1.5, -0.3), *d* = 3.23] whereas target capture was strongly positively correlated with NT 3D-MOT performance gains [$r_S$ (16) = 0.655, (CI: -0.1, 1), *d* = 1.72]. No other correlation appeared to be substantially meaningful (see Appendix 1).

***Physical Activity.***

The total time of physical activity for the duration of the study was 84.22 hours (*SD*: 25,17) for the intervention group and 76,44 hours (*SD*: 26,05) for the control group. The effect of the difference between the physical activity of both groups was small to medium *d* = -0.3 (CI: -1, 0.4)

## DISCUSSION

The current study addressed the question of whether a 10-week training program with the NT 3D-MOT evokes transfer effects to visual and executive functions in elite soccer players. The absence of any meaningful changes indicates a lack of further-transfer to other not directly trained visual and executive functions except for task-specific effects and near-transfer to skills of NT 3D-MOT and MOT. The previous comparison of visual and executive functions and their theoretical requirement in NT 3D-MOT did not indicate any common ground (see Appendix 2), which seems to explain the lack of meaningful further-transfer. Moreover, this lack also appears to be based on the specificity of the training task which includes some aspects of dynamic soccer situations but does not cover the perception and action combinations of these situations (Romeas et al., 2019). Thus, it could be argued that this dearth of several broad perception and action combinations may be one of the reasons for the absence of any further-transfer which is in line with a current review (Hadlow et al., 2018). This lack of further-transfer to executive functions is in line with previous studies of Moen et al. (2018) and Fleddermann et al. (2019). However, increases in sustained attention and processing speed were found in the latter study. The investigation of Parsons et al. (2016) is in contrast to the current findings as improvements in several cognitive functions were found. Though, the task-specific effects and near-transfer to the NT 3D-MOT and MOT are in line with previous studies of Fleddermann et al. (2019) and Faubert (2013) which demonstrate that the athletes have an extraordinary capacity for learning an unpredictable and complex visual tracking task (Faubert, 2013). Moreover, this practice improvement in NT 3D-MOT and MOT underlines that cognitive functions are trainable from a fundamental standpoint although this malleability may only be achievable in terms of near-transfer training effects (Bryck & Fisher, 2012; Fields, 2015). Consequently, future studies should integrate brain-scanning tools to investigate functional or structural adaptations of the brain like more efficient neural processing as these are the building stones of performance improvements.

Overall, it seems to be the case that the NT 3D-MOT only evokes task-specific practice effects with little near- and no further-transfer to other visual and executive functions which is in line with a previous review (Diamond & Ling, 2016). Further, it might be stated that the improvements of NT 3D-MOT and its transfer to soccer-specific decision making (Romeas et al. 2016) are mainly originated in the task-specific MOT enhancement and not due to changes of visual abilities or cognitive processing. This lack of further-transfer substantially challenges the statement that the NT 3D-MOT is a "Gold Standard Cognitive Enhancer" (Parsons et al., 2016) which enhances executive- and some visual functions as the visual field, depth perception and attention (Faubert & Sidebottom, 2012, Parsons et al., 2016). Additionally, the absence of further-transfer confirms the vast amount of studies showing that executive functions must be targeted specifically in training in order to improve them (for review see Diamond & Ling, 2016).

Nevertheless, even the MOT ability alone seems to be crucial for dynamic sports (Mangine et al., 2014; for a meta-analysis see Scharfen & Memmert, 2019a) and its training is assumed to lead to aforementioned soccer-specific decision-making improvements at least in amateur athletes (Romeas et al., 2016). However, it needs to be taken into consideration that this type of strict single-task NT 3D-MOT practice only depicts the first step in the training progression plan of the NT 3D-MOT. The next steps after an initial familiarization phase in sitting and standing positions would be balancing and dual-tasking with sports-specific movements. In terms of future practical application, it is highly interesting if those further progression steps yield larger further- or even far-transfer effects. A first dual-task study indicates the general superiority of dual- compared to single task-training with the NT 3D-MOT (Romeas et al., 2019).

Furthermore, elite athletes are already performing on a high cognitive level. Therefore, even small improvements like those found in the current investigation could be a meaningful change in a real game situation (see Change in Table 1). This high cognitive performance level which is mostly present in cross-sectional studies of elite soccer players seems to be advantageous regardless of whether this is based on a matter of selection or implicit training (i.e. nature vs nurture).

The covariate physical activity differed only with a small to medium effect size which suggests that changes may be based on the cognitive training for the most part. Further, the second rationale of the study addressed the controversy of the two opposing theories aiming to explain individual differences in training-related performance gains (i.e. magnification vs compensation theory; Karbach & Unger, 2014). The strong negative correlation of NT 3D-MOT performance, perception span and target capture (reversed performance scale – depicting a strong positive correlation) in the pretest and NT 3D-MOT performance gains may favor the compensation theory. This theory assumes that individuals with lower baseline performance have a more considerable gain potential from cognitive training as their room for improvement may be relatively large.

Concerning the practical applications, it can be stated that the NT 3D-MOT is a useful tool to enhance the athlete's multiple-object-tracking skill which alone seems to be crucial for dynamic sports (Mangine et al., 2014; Scharfen & Memmert, 2019a). Nevertheless, the present findings imply that the single-task NT 3D-MOT training is not suitable for enhancing other visual or executive functions. Future studies are required to examine the possible transfer effects of a dual-task training mode. As the absence of further transfer adds to the vast amount of previous studies emphasizing the need to target executive functions to improve them directly it is necessary to include specific elements of these executive functions in the training regime. Specifically, the integration of these elements in on- and off-pitch training could intensify the effects of the natural advantage/selection of players with superior executive functions or the implicit training of them by playing soccer as observed in elite players. Thus, future studies investigating sport-specific cognitive training, specifically targeting certain elements of executive functions either on- or off-pitch are highly relevant as the field of cognitive performance enhancement in elite-athletic populations is still in its infancy. Further, the NT 3D-MOT seems to be a helpful training tool to improve the multiple-object tracking skill, especially of players which have a deficit in this domain.

Some limitations of the present study also need to be acknowledged. In general, the sample size is not big enough to draw final inferences which can be seen in the relative breadth of the 95% confidence intervals. Based on these findings, future studies should replicate this with a larger sample and with a second intervention phase, including dual-task NT 3D-MOT training. Furthermore, it needs to be taken into consideration that other possible adaptions of the athlete's brain cannot be ruled out (e.g. higher degree of myelination, more efficient energy usage) as only the performance output of the brain but not the underlying processing mechanisms had been tested. Karbacher and Unger (2014) proposed such tools and the study of Parsons and colleagues (2016) found altered brainwaves as a function of the NT 3D-MOT training which matches current findings of activity-dependent plasticity in the brain (Fields, 2015). Moreover, although the covariate physical activity was analyzed, other factors like some players being youth national players were still present, which could have influenced the outcome.

## Conclusion

Studies on the effectiveness and transfer of lab-based cognitive training programs in elite sports are scarce. Therefore, this study is one of only a few investigating transfers to a broad variety of visual and executive functions. Generally, results hint at the plasticity of these functions and their improvement as a function of additional lab-based training. The outcomes showed meaningful near-transfer benefits to the trained ability (i.e. MOT) besides minor improvements in a few other tasks (i.e. inhibition, visual clarity). Nevertheless, none of the other parameters showed meaningful further-transfer improvements or no improvements at all in the intervention group compared to the control group. The results may reduce the possible areas of further-transfer of the NT 3D-MOT and underpins the necessity of brain-scanning tools in future studies examining training effects of visual and executive functions. Investigations of transfer effects of NT 3D-MOT dual-task training are needed to further rule out its field of application for practitioners.

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**Appendix V.I** Correlations $r_s$ between pre-test performance (i.e. executive and visual functions) and NT 3D-MOT performance gains. CI = Confidence Interval, For all measurements, the number of participants was equal (n = 16).

| | | **NT Gain** |
|---|---|---|
| NT 3D-MOT | Correlation coefficient | -.851 |
| | CI | -1.5, -0.3 |
| Attention Window | Correlation coefficient | -.287 |
| | CI | -0.8, 0.6 |
| Working Memory | Correlation coefficient | -.286 |
| | CI | -0.5, 0.6 |
| Metacognition | Correlation coefficient | -.373 |
| | CI | -0.5, 0.46 |
| Cognitive Flexibility | Correlation coefficient | .021 |
| | CI | -1.1, 0.2 |
| Visual Clarity | Correlation coefficient | -.180 |
| | CI | -0.5, 0.5 |
| Contrast Sensitivity | Correlation coefficient | .111 |
| | CI | -0.37, 0.6 |
| Depth Perception | Correlation coefficient | .234 |
| | CI | -0.7, 0.12 |
| Near-Far Quickness | Correlation coefficient | .108 |
| | CI | -0.4, 1.4 |
| Target Capture | Correlation coefficient | .655 |
| | CI | 0.12, 1.1 |
| Perception Span | Correlation coefficient | -.164 |
| | CI | -1.5, -0.05 |
| Multiple-Object Tracking | Correlation coefficient | -.353 |
| | CI | -0.73, 0.15 |
| Inhibition | Correlation coefficient | .238 |
| | CI | -.185, 1.2 |
| Reaction | Correlation coefficient | -.028 |
| | CI | -0.92, 0.26 |

**Appendix V.II** Comparisons of definitions of executive and visual functions and requirements in the NT 3D-MOT (definitions based on 1) executive functions: Diamond (2013); Miyake & Friedman (2012), 2) visual functions: Erickson et al., (2011))

| **Executive Function** | **Definition** | **Requirement in NT 3D-MOT** |
|---|---|---|
| Working Memory | holding information in mind and manipulating it | Not required, no manipulation |
| *(Short-Term Memory)* | *just holding information in mind* | *Eventually required* |
| Cognitive Flexibility | changing perspectives or approaches to a problem, flexibly adjusting to new demands, rules, or priorities (as in switching between tasks) | Not required, no changes |
| Inhibition | | |
| Response Inhibition | deliberate overriding of dominant or prepotent responses | Not required, no overriding |
| Cognitive Inhibition | Inhibition of thoughts/ memories | Eventually required |
| Selective or Focused Attention (Interference control) | Inhibition at the level of attention | Eventually required |

| | | |
|---|---|---|
| Metacognition | the ability to reason, problem-solving, and to see patterns or relations among items | Not required |

| **Visual Function** | **Definition** | **Requirement in NT 3D-MOT** |
|---|---|---|
| Visual Clarity | visual acuity for fine details at a distance | Not required, no fine details |
| Contrast Sensitivity | visual system's ability to process spatial or temporal information about objects and their backgrounds under varying lighting conditions | Not required, no varying lighting conditions |
| Depth Perception | determining distance and spatial localization of an object | Not required, only tracking but not determining localizations at different distances |
| Near-Far Quickness | ability of quick accommodative–vergence facility in binocular saccadic responses to images at near and far distances | Not required, no quick near-far changes |
| Target Capturing | ability of the visual system to resolve detail when there is relative movement between the target and the observer | Not required, movement is present but no need to resolve in detail |
| Perception Span | ability to remember and recreate visual patterns | Not required as the visual pattern is not static but constantly changing |
| Reaction time | ability to react and respond to a simple visual stimulus | Not required, no quick reaction required |
| Attention Window | individual attention breadth on diagonal, horizontal and vertical axis | Eventually required |