PERCEPTUAL-COGNITIVE ASSESSMENTS IN FOOTBALL

This dissertation is submitted for the degree of
Doctor of Philosophy
by
Adam Francis Beavan
Bachelor of Exercise and Sport Science (Hons)

Institute of Sports and Preventive Medicine
Saarland University
Saarbrücken, Germany
&
Sport and Exercise Discipline Group, Faculty of Health
University of Technology
Sydney, Australia.

2020

This thesis is presented for the award of a Doctor of Philosophy (Sports Medicine) from the Philosophical and Medical Faculty, Saarland University, Saarbrücken, Germany in conjunction with the Faculty of Health, University of Technology Sydney, Australia

"Grit can be defined as passion and perseverance for especially long-term goals."
Angela Duckworth

"Anything wise in these pages you should credit to the many experts who preceded me. Anything foolish, assume it is my error."
James Clear, Atomic Habits, Page 9

Declaration

I, Adam Francis Beavan, declare that this thesis, is submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy in the Institute of Sport and Preventive Medicine, Saarland University (Germany) and at the University of Technology Sydney (Australia) in the Sport and Exercise Discipline Group, Faculty of Health, conducted jointly under the Memorandum of understanding between both institutions as part of an international joint PhD program.

This thesis is wholly my own work as the sole author unless otherwise referenced or acknowledged. As such, I also certify to the best of my knowledge and belief that this thesis does not:

i. incorporates any material previously submitted for a degree or diploma in any institution of higher education without acknowledgement;

ii. contain any material previously published or written by another person; where due reference is made in the text; or

iii. contain any defamatory material

I also acknowledge that this research was supported by the German Football Association (Deutscher Fußball-Bund).

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree at any other academic institution except as fully acknowledged within the text. This thesis is the result of a Collaborative Doctoral Research Degree program with Saarland University and the University of Technology Sydney.

I also grant permission for the libraries at Saarland University and University of Technology Sydney to produce duplicate copies of my thesis as required.

Adam Francis Beavan Date:

Acknowledgements

For the first two years of my PhD, my time was split between UdS and UTS, and the last year I was embedded in the football club TSG 1899 Hoffenheim. I am grateful for the unique contributions that each institution gave me throughout this dissertation, and for hosting me during my studies.

For the staff at Saarland University, with special mention to my supervisors Sabrina Skorski and Tim Meyer, thank you for providing me with this opportunity to conduct my PhD. I am grateful that you thought I was the right candidate for the position, and I hope that my efforts have confirmed such. You provided me with an office full of my now best friends, a connection to both a Bundesliga club and the German Football Association and gave me the independence to allow me to find my own way through this journey. Thank you for providing me the opportunities to present my work across the world, which has allowed me to not only grow my personal skills, but an international network. Lastly, thank you for the additional effort outside the supervision roles, all starting with the famous ‘Skorski Tour’ to tickets to the biggest international football games. Thanks to all the other staff that were always friendly and patient with my German A1 abilities.

To all of the international PhD’s that shared the office with me over the years, we’ve had a right laugh. The office was a nightmare for productivity but a dream for friendship. First of all, to Ida (IDZY), you’ve been my rock. I am so grateful that it was you that did this journey step by step with me from start to finish. I would be lost without you by my side every day, especially with paperwork, airports and all the life advice you have given me. But I introduced you to Dan and took you around Australia, so I think we are almost equal! To Dan (the unofficial PhD crew member), the universe meant for us to meet at Murphy’s that day. Rigatoni, red wine, and Catan – need I say more!? To Ross (the chief PhD), thanks for just being a great friend. You stepped up to the plate for being that guy that everyone can go to just to get things off their chest, and that really helped me in my low times. To Bobby (Vapiano’s most loyal customer), you were always there for a laugh, distraction, and a role model of work ethic and postural control. Keep slamming tables and living the dream life as a sport scientist. To Emiel (the office DJ), you were always there to give rational advice and to put me in my place, I look forward to the next

Octoberfest with you. To Denny (Big Narsty), your laugh was infectious. You have the potential to become the best player agent, signing all 5th division Eastern European players to Leicester City. To Mat (Beers & Tears Co-founder), you're a role model for everyone to keep pursuing their passion, to stay adventurous, and to not take one's self so seriously. To Ludwig (congratulations), your passion and dedication for improving research in your topic is unchallenged. I look forward to continuing our friendship into the new era of our careers, even if you don't. To Monica (Chica), thanks for laughing at the same joke I told everyday making me feel like a real comedian… "dad the moves"! Last and certainly least, to Chris (Thompson), we became brothers bonded by the same unique sense of humour and outlook on life. Thanks for making my time in SB the funniest years of my life. I think I spent more time and wrote more words on WhatsApp with you than I ever did on my PhD.

To my supervisor at the University of Technology Sydney, Job Fransen, this five year-long journey under your guidance is one that I will forever be grateful that I travelled with you on. You are a great leader. One that has enough confidence in your own ability to feel validated, not threatened, by the success of those that you are leading. You encourage, inspire, teach, and anticipate success for all your students. A famous quote I remember you saying from many years ago was "my students should become experts in their field and then teach me something by the end of their thesis", and I hope I've done that. You are a 'Thomas Derale' of this world, and only those who have read the book *The Big Five For Life* will be able to appreciate such a comparison. To the staff and fellow students (i.e. the work horses) at UTS, I enjoyed the family-like environment that everyone created during my time there.

Being at a university, while necessary, wasn't enough. It didn't allow me to judge the importance of the principles in the world beyond the four walls of the university office. I spent the first two years periodically visiting and collecting my data embedded at the football club TSG 1899 Hoffenheim and was fully embedded in last year of my PhD. This gave me a lot of great opportunities to discuss ideas, results and practical implications for the studies with the staff and players who compete at the highest level of European football. Special mentions go to Jan Spielmann for being foremost my friend and second the coordinator of all my research. This PhD would not have been possible without you and your German efficiency. Additionally, to my supervisor Jan Mayer, I've enjoyed the

opportunity to put some of your ideas to the test of science. Your innovative ideas and motivation to overcome the historical constraints of what is ‘normal’ in football practice has really been a joy to watch and play a small part in. Other mentions at the club are Sascha, Sandra, Marcel, Chris, Paul, Stefan and Fabian, who have collectively shown me that practitioners and scientists often share the same goal, yet their methods on how to get there often differ largely – and that is what makes a healthy competition forcing us to strive to be better in our fields.

To the German Football Association with special mentions to Thomas Hauser, Roman Prinz and Oliver Bierhoff, thank you for playing an important role in allowing me the opportunity to come to Germany to do my PhD. The many opportunities to discuss and brainstorm ideas from meetings as big as the Think Tanks to small one-on-one talks over coffee at the headquarters. It was a pleasure to be able to work and learn alongside the DFB and be a part of the new DFB-Akademie.

Thank you to my mother Suzelle for allowing me to have a stable education throughout my upbringing despite the chaos that surrounded us. A mother’s love is a powerful thing, and you showed me that love, passion, and being a good person always overcomes all adversity. I relied on these lessons to overcome the many hurdles that I faced during my time overseas. To my older brother Alexander, watching you face the nightmarish physical and mental demands that the army placed on you made me rethink if writing words on paper in an airconditioned office is really something to complain about, its rather a privilege. To my sister Chelsea, you showed me that moving overseas and leaving your comfort zone brings new opportunities and complaining about still being students in our late 20’s brought us closer together. To my not-so-little brothers, I hope that I have showed you that higher education is the key to success, and that I have inspired you both to pursue your dreams no matter how big they seem.

Finally, to my partner Sarah, you’ve put life into a new perspective for me, shifting my priorities to be more about living life to its fullest rather than the one-dimensional working mindset I once had. Your positivity, kindness, love and support were exactly what I needed to push through the rest of this thesis. Thanks for being my ‘ride or die’ woman in this crazy journey.

The format of this thesis is aligned with the ‘Thesis by Publication’ format as per the standards of both Saarland University and the University of Technology Sydney.

List of Publications Incorporated into this Thesis

The below list outlines the published, in press or in preparation studies that are incorporated into this thesis. The studies listed below are presented in full in the following Chapters of this thesis.

Chapter 1:

i. Beavan, A. (2019). Extraordinary Tools Require Extraordinary Evidence. *Science and Medicine in Football*, 3:4, 263-264, https://doi.org/10.1080/24733938.2019.1678948

Chapter 3:

i. Beavan, A., Spielmann, J., Mayer, J., Skorski, S., Meyer, T., & Fransen, J. (2020). The Rise and Fall of Executive Functions in High-Level Football Players. *Psychology of Sport and Exercise.* https://doi.org/10.1016/j.psychsport.2020.101677

Chapter 4:

i. Beavan, A., Fransen, J., Spielmann, J., Mayer, J., Skorski, S., & Meyer, T. (2018). The Footbonaut as a new football-specific skills test: reproducibility and age-related differences in highly trained youth players. *Science and Medicine in Football, 3*(3), 177-182. https://doi.org/10.1080/24733938.2018.1548772

Chapter 5:

i. Beavan, A., Chin, V., Spielmann, J., Mayer, J., Skorski, S., Meyer, T., & Fransen, J. (in press). A longitudinal analysis of the executive functions in high-level football players. *Journal of Sport & Exercise Psychology.*

Chapter 6:

i. Beavan, A., Fransen, J., Hanke, L., Spielmann, J., Skorski, S., Mayer, J., & Meyer, T. Using Stroboscopic Vision to Restrict Visual Feedback in a Football Specific Skill Assessment. *In preparation.*
ii. McGuckian, T., Beavan, A., Mayer, J., Chalkley, D., Pepping, GJ (In press). The association between visual exploration and passing performance in high-level U13 and U23 football players. *Science and Medicine in Football.*

Appendix:

i. Beavan, A., Spielmann, J., Mayer, J., Skorski, S., Meyer, T., & Fransen, J. (2019). Age-Related Differences in Executive Functions Within High-Level Youth Soccer Players. *Brazilian Journal of Motor Behavior*, *13*(2), 64-75. https://doi.org/10.20338/bjmb.v13i2.131
ii. Beavan, A., Spielmann, J., Mayer. (2019). Taking the First Steps Towards Integrating Testing and Training Cognitive Abilities Within High-Performance Athletes; Insights from a Professional German Football Club. *Frontiers in Psychology, 10,* 2773. https://doi.org/10.3389/fpsyg.2019.02773

List of Conference Presentations

The below list outlines conference presentations at which the findings of this thesis were presented.

i. Beavan, A., Fransen, J., Spielmann, J., Skorski, S., Mayer, J., Hauser, T., Meyer, T. (2019). 'The Rise and Fall of Executive Functions in Athletes', paper presented at the German Olympic Sports Federation's (DOSB) Annual Conference for Sports Psychology, Hoffenheim, 25th October.

ii. Beavan, A., Fransen, J., Spielmann, J., Skorski, S., Mayer, J., Hauser, T., Meyer, T. (2019). 'The Rise and Fall of Executive Functions in Athletes', paper presented at the 15th European Congress of Sport & Exercise Psychology, Münster, 15-20 July.

iii. Beavan, A., Fransen, J., Hanke, L., Spielmann, J., Skorski, S., Mayer, J., Hauser, T., Meyer, T. (2019). 'High Level Football Players' Ability to Use Implicit Information as Affordances for Action', paper presented at the European College of Sport Science, Prague, 2-7 July.

iv. Beavan, A., Fransen, J., Hanke, L., Spielmann, J., Skorski, S., Mayer, J., Hauser, T., Meyer, T. (2019). 'Executive functions in elite level football players', paper presented at the World Congress of Science and Football, Melbourne, 3-7 June.

v. Beavan, A., Fransen, J., Hanke, L., Spielmann, J., Skorski, S., Mayer, J., Hauser, T., Meyer, T. (2018). 'Using stroboscopic vision to restrict visual feedback in a football specific skill assessment', paper presented at the Australasian Skill Acquisition Network conference, Sydney, 15-16 November.

vi. Beavan, A., Fransen, J., Hanke, L., Spielmann, J., Skorski, S., Mayer, J., Hauser, T., Meyer, T. (2018). 'Using stroboscopic vision to restrict visual feedback in a football specific skill assessment', paper presented at the European College of Sport Science, Dublin, 4-7 July.

Preface

This dissertation is a synthesis of the research that dates back almost a hundred years as well as the most recent findings that scientists have made, and everything in between. My contribution, I hope, is to connect the ideas of various research domains both within and external to sport, and incorporate the philosophies shared by the practitioners that have been implementing such ideas into practice for many years. Together, this dissertation should present a clear fusion of the research and presents the findings in a way that is highly actionable for both researchers and practitioners.

I wrote this thesis and all the manuscripts included within in many countries from Europe to Australia, in cafés and hospital rooms, in houses and hotels, in universities and football club offices, at work and on holiday, from morning to night, and while travelling in trains, planes and cars. I believe that I was always influenced by my environment, and I offer the reader a choice to imagine which environment I was immersed in when writing various sections of this thesis.

Last, external books that inspired me to finish my PhD me were many, but notable mentions were Atomic Habits by James Clear, Thinking Fast and Slow by Daniel Kahneman, and The Big Five For Life by John P. Strelecky.

Table of Contents

List of Symbols and Standard Abbreviations

AIC	Akaike’s Information Criterion
ACL	Anterior Cruciate Ligament
ANOVA	Analysis of Variance
Au	Arbitrary Units
Bundesliga	Germany’s 1st division in football
C	Congruent
cEV	Conditional Explained Variance
CI	Confidence Intervals
CV	Coefficient of Variation
DMGT	Differentiated Model of Giftedness & Talent
DT	Determination Test
EFs	Executive Functions
ES	Effect Size
Exp	Years of experience playing football
F	F-Value
Football	Association Soccer
Hz	Hertz
IC	Incongruent
IMU’s	Inertial Measurement Units
IQ	Intelligence Quotient
IQR	Interquartile Range
Km/hr	Kilometres per hour
LCD	Liquid Crystal Display
LEDs	Light Emitting Diodes
LS	Less Skilled
LSPT	Loughborough Soccer Passing Test
m	Meters
MANVOA	Multivariate Analysis of Variance
mEV	Marginal Explained Variance
ms	milliseconds
n	Number of participants

NFL	National Football League (American Football)
P	P-Value
PCRTT	Precued Choice Response Time Task
PT-Test	Physical and Technical Test
r	Pearson’s Correlation
RM-MANOVA	Repeated Measures Multivariate Analysis of Variance
S	Skilled
s	Seconds
SD	Standard Deviation
SSRT	Stop Signal Response Time
USD	US Dollars
VEA	Visual Exploratory Actions
VTS	Vienna Test System
y	Years
2D	Two-Dimensional
3D	Three Dimensional
%	Percentage
o	Angle
Δ	Delta (Change)

List of Tables

List of Figures

Abstract

Introduction:

Assessments with varying levels of perceptual information or action fidelity are commonly used in the detection and identification of talent in football. Common performance assessments can range from either highly sport-specific environments with players being immersed in a realistic environment and interacting with a football (i.e. domain-specific, high ecological validity), to players sitting in front of a computer responding to various shapes and colours with no sport-specific information presented (i.e. domain-generic, low ecological validity). Many testing batteries measure athletes with a multitude of different tests that are placed along various points on ecological validity continuum. However, very few of these assessments are sufficiently validated. For the assessments that attempt to closely replicate the perception-action coupling demands experienced in football game play, there are many conditions that must be met before it can be used in future research and practice. On the other side of the spectrum, it remains contentious whether using assessments that intentionally remove ecological validity from their environments has merit. These non-sport specific assessments attempt to measure the general cognitive abilities of athletes, and many researchers have advocated their usefulness in talent identification programs. Therefore, the collection of aims within this dissertation was three-fold: i) to investigate both the domain-generic and domain-specific perceptual-cognitive abilities of all athletes (i.e. academy to senior players) in order to understand what perceptual-cognitive abilities athletes exhibit, and what factors (i.e. environment and heritable) contributed towards their cognitive profile, ii) to track both domain-specific and domain-generic abilities longitudinally in order to understand their relationships with increased exposure to football training, and iii) to learn from the limitations of the domain-specific skills assessment and incorporate new technologies in order to gain a further insight to investigate how emerging technologies could help to develop more representative assessments.

Methods:

To understand the between-group differences of domain-generic and domain-specific abilities across the youth developmental period of athletes, a variety of independent studies were undertaken. First, 343 male players (age: 10.34 – 34.72 years; playing

experience: 5 – 22 years) from the U12-Senior age groups of a professional German football club were recruited. Age, experience and playing position were recorded to examine which factors contributed more to the development of domain-generic abilities (Chapter 3). Players participated in four generic cognitive tasks aimed at measuring higher-level cognitive functioning: a precued choice response-time task, a stop-signal reaction-time task, a sustained attention task, and a multiple-object tracking task. Second, a new football-specific skills test was used to measure the domain-specific abilities of the athletes throughout adolescence, and the reliability and age-discriminant validity of this new domain-specific skills test was investigated (Chapter 4). Third, 304 players from the same cohort as Chapter 3 had their data analysed longitudinally to track the longitudinal development of both domain-generic (assessments from Chapter 3) and domain-specific (assessment from Chapter 4) abilities across three seasons (Chapter 5). Lastly, the final investigation of the dissertation was divided in two parts to explore how to develop more representative task designs within the football specific skills assessment used in the previous chapters. Accordingly, Chapter 6a) 85 amateur male participants (19.5 ± 5.4 years old; 13.1 ± 6.0 years playing football) completed two sessions in the skills assessment task under two different visual conditions: stroboscopic and full vision Participants were subdivided into skilled (S: top 50%) and less-skilled (LS: bottom 50%) groups using their point score from the full vision condition. Chapter 6b) Exploratory head movements of fourteen U13 and thirteen U23 high-level football players were recorded with a head worn inertial sensor in the skills assessment task, from which the count, frequency and excursion of head movements were extracted before and during ball possession investigate whether visual exploratory action is associated with passing performance.

Results:

Chapter 3 first demonstrated that a negatively accelerated curve generally best described the relationship between age, experience and domain-generic abilities. Age and experience only explained a very low to moderate proportion of the variance in EFs (marginal explained variance ranged between 2 and 57%). Furthermore, although Chapter 4 revealed that the new domain-specific skills test yielded acceptable test-retest reliability for the correct number of passes in a target (CV = 7.5-11.1; $r = 0.48$; $p<0.001$) and the speed at which they completed each trial (CV = 2.6-5.1; $r = 0.70$; $p<0.001$), the assessment was not able to differentiate between athletes over the age of 15. This plateau

in both the developmental trajectories of domain-generic (Chapter 3) and domain-specific (Chapter 4) abilities was confirmed in the longitudinal study (Chapter 5), revealing that a performance plateau was apparent for domain-specific abilities during adolescence (i.e. 15 years old), whereas domain-generic abilities improved into young adulthood (i.e. 21 years old). Consequently, a further investigation into more representative task design had merit, where Chapter 6a) reported that restricting athletes' visual feedback in the football skills assessment impacted time in both S and LS groups equally (S: 0.21s; LS: 0.18s; p=0.543), but S athletes' accuracy (S: 11.7%; LS: 0.4%; p<0.001) were significantly more affected compared to full vision conditions. Lastly, Chapter 6b) reported that the variables that best explained faster performance were a higher number of head turns before receiving the ball, and a lower number of head turns when in possession of the ball, which older athletes perform better than younger athletes.

Discussion/conclusion:
Overall, the investigation into domain-generic assessments across Chapter 3 and 5 found that athletes improve their performance during late childhood until reaching adolescent (i.e. average age of 15 years old) and was independent of how many years of experience playing football or which position they played on the field. As the developmental trajectories of high-level football players' domain-generic abilities reflected those observed in general populations' despite long-term exposure to football-specific training and gameplay, this questions the relationship between high-level experience's capacity to improve domain-generic abilities and challenges the validity of including non-sport specific assessments as a measure of football performance potential in high performing athletes. Lastly, despite the best efforts to use highly technical assessments to measure football skills in Chapter 4 and 5, the assessments may have under-represented the perceptual or action components necessary to allow athletes to demonstrate their expertise. Thus, more studies that aim to improve on the task designs of assessment tools has merit, and future studies could build off the foundations from the studies within Chapter 6 [i.e. stroboscopic glasses (6a) and head movement sensors (6b)] as methods to expand on the representativeness of assessment tasks.

Navigation of Thesis

Athletes are subjected to continuous performance assessments from the time they enter a high-performance training environment until the day they leave. Throughout their career span, athletes will be repetitively subjected to comparisons both on age and playing level grouped norms on all aspects of their performance. Interestingly, many of the performance assessments commonly used in football have yet to be supported by science; tools that are generally implemented first by practice with science proceeding with justification of the methods. Therefore, this thesis adds important findings that contribute to the debate of whether measures of cognitive abilities should be implemented in high-performance sport.

Chapter 1 provides a general introduction to the thesis, a description of the theoretical background of various performance assessments, and the applicability and proposed value of these assessments to explain expertise by reviewing the extant literature both within and external to a sporting domain. Furthermore, a probing investigation is also included to understand if there are any observable relationships between age and generic cognitive abilities in football players that could provide a rational towards continuing the investigation of using non-sport specific assessments.

Chapter 2 provides a statement of problems and related aims of the experimental studies within this thesis.

Chapter 3 contributes to the nature vs. nurture debate in a large cohort of high-level football players by analysing the contribution that age, years of experience playing football and playing position have on explaining performance on generic measures of cognition.

Chapter 4 explores the reliability and age-discriminant validity of a new sports-specific skills assessment task and provides benchmark performance data of high-level football players performances throughout late childhood into young adulthood.

Chapter 5 is a rigorous statistical approach that examines how players develop their domain-specific and domain-generic perceptual-cognitive abilities throughout late childhood into early adulthood in a three-year longitudinal manner.

Chapter 6 contains two separate investigations that examine the perceptual abilities of how athletes receive information in the football-specific skills assessment and discusses the relevance of adapting existing equipment to better match the perception or action demands of football. Both studies implemented technology in the skills assessment task validated in Chapter 4 in attempt to improve the representative task designs of assessments in sport. The first study within this chapter uses stroboscopic glasses technology to vary the amount of visual input that athletes require to perform their football specific movements, providing a further understanding of perception-action coupling in high-level and lower-level athletes. The second study within this chapter discusses a study that used inertial measurement units placed on the head of athletes to examine the relationship between visual exploratory head movements prior to ball possession and with ball possession, and the effect on subsequent performance with the ball.

Chapter 7 provides a general discussion of the thesis, including a summary of findings from each chapter, research limitations, and an outline of future directions for this field of research.

Chapter 8 contains the appendices, which two full manuscripts can be found amongst other miscellaneous documents. The first manuscript is the preliminary study mentioned in Chapter 1, and the second manuscript is an opinion piece written about the implementation of a cognitive assessment battery within a professional football club.

Chapter 9 contains all the full citations of the references used throughout this dissertation.

Chapter 1: General Introduction

Anyone who is familiar with classic films like Never Been Kissed, The Breakfast Club or Mean Girls will know that high school and college athletes are generally portrayed as ‘jocks’. These characters stereotypically display all the physical capabilities, such as being tall, strong, muscular and fast, however these physical traits come as a consequence of having a low intellect. The athlete characters further separate themselves from any form of intelligence by bullying the ‘nerds’ of the group; characters that display low physical capabilities but have a high level of intelligence. Therefore, the media has created a well-known concept between brain vs. brawn, being that athletes are physically superior but not intelligent, and people who are intelligent are not physically superior.

Furley & Wood (2016) stated that perhaps the ‘jocks vs. nerds’ dichotomy may be a potential reason for the late onset of recognizing the importance of cognitive abilities in athletes compared to their physical characteristics. Most talent identification batteries have emphasized physical or technical characteristics of athletes, where the consideration towards the cognitive abilities of athletes has been largely overlooked. Yet for many years, research in a sporting domain has continuously refuted this stereotype, demonstrating that athletes in fact hold superior cognitive abilities alongside their physical abilities compared to the non-athletic populations.

The concept of talent identification is our first introduction to another key theme in this thesis: performance metrics. Although it is popular for an individual in their job to be measured on many performance assessments in order to demonstrate their abilities to perform a certain task, performance rankings generally stop after the individual is finished with their studies. For example, a chef generally is not further measured on standardized tests that aim to compare their abilities against other chefs once they have left cooking school. Similarly, you do not know whether the accountant handling your taxes ranks above or below average compared to their colleagues, or how good the dentist that you visit is on their ability to fit braces for your child. Word of mouth or reviews online are uncontested by other forms of performance rankings, but these are merely subjective guidelines rather than standardized assessments that hundreds of other dentists have completed to be measured against each other on. Sport, however, are amongst the few fields where performance-based assessments are continuously used throughout someone's career. Athletes are repetitively measured and compared to normative values on all aspects of their performance, including their physical, tactical, technical, social, psychological abilities, and now recently, cognitive measurements are being introduced.

A few major incentives for this barrage of measurements is to assess the well-being of the athlete, to avoid the risk of injury and to track improvements if an intervention is working or not. However, another major incentive and a core theme of this dissertation, is to understand what cognitive abilities an elite athlete yield and if these abilities can help explain why these athletes reached the highest level of attainment in their domain. Examining what criteria an athlete must possess in order to perform at various levels of performance allows for the search for athletes that already presently demonstrate these abilities, or to search for younger athletes that demonstrate the potential to express their abilities to such an extent in the coming years.

A possibility for increasing interest into the cognitive abilities of athletes comes from the rapid increase in demand to think fast. For example, in football, the German national team's sport psychologist Dr. Hans-Dieter Hermann reported that the average per-player ball possession time for the German team was 2.9 seconds in the 2006 World Cup and 0.9 seconds in the 2014 World Cup (Katwala, 2016). In other words, this is more than a threefold decrease in time players took to complete the action encompassing the decision-making aspect, all in just eight years. Thus, as athletes are reaching the physical ceilings of the human body with regards to speed, endurance and strength, other avenues are being investigated in search of other indicators or underlying factors that may help explain why some athletes reach the highest-level of competition, and why others do not.

In sum, athletes are constantly subjected to normative comparisons on all aspects of their performance. As the demands of football are constantly becoming more challenging and pushing athletes to the limits, the new age of athletes will have to be both physically and mentally faster, stronger and more resilient. The remainder of the general introduction will explain the various methods that researchers and practitioners have used to measure a myriad of aspects of an athletes' cognitive abilities, provide an overview of the literature on the underlying theories that either support or argue against these assessments, and further discusses in-depth whether assessments that test the functionality of the central nervous system can truly predict the next great athlete.

1.1 Theoretical background: perceptual-cognitive expertise

A requirement for successful performance in team sports is making consistently fast and accurate decisions during team sport games. Decision-making is a real time process in which athletes rapidly process a large amount of information in order to carry out a functional movement solution that take into account the constraints imposed by the environment, the individual and the intended task (Mann, Farrow, Shuttleworth, Hopwood, & MacMahon, 2009). Therefore, it is crucial that athletes refine their ability to extract important information while negating unimportant information (Williams & Ericsson, 2005). The underlying mental construct is known as perceptual-cognitive skills. Perceptual-cognitive skill is the process of acquiring environmental information, integrating it with existing knowledge, and formulating an appropriate response (Marteniuk, 1976). Athletes rely on this process to make rapid, accurate decisions based on the retrieval and processing of information from a dynamic environment (Nédélec et al., 2012). Therefore, the acquisition of perceptual-cognitive skill is an essential process in a sports setting where athletes must react to their environment based on the information provided and make an action which will have a direct influence on the outcome of the game (Williams, Ward, Knowles, & Smeeton, 2002).

The ability to enhance the perceptual-cognitive skill of an athlete is important not only for sport scientists, but for coaches and athletes themselves as it may lead to an increase in performance. Hence, an extensive body of research has focused on the factors underpinning perceptual-cognitive expertise in sport (Mann, Williams, Ward, & Janelle, 2007; Travassos, Araújo, et al., 2013). The existing studies that examine the factors underpinning perceptual-cognitive expertise in sport generally fall within one of two theoretical frameworks: the expert performance approach or the cognitive component skill approach.

The more common framework is the expert performance approach. This approach is based off the theoretical understanding that the ability to rapidly extract and process relevant information is often a result of an extensive knowledge base; a foundation of game-specific knowledge that has been progressively developed over years of engaging in sport related activities (Ericsson & Ward, 2007). Therefore, a large body of research has focused on measuring athletes' domain-specific processes (i.e. anticipation, attentional focus, pattern recall etc.) using assessments that attempt to mirror the environmental constraints of a game (Mann et al., 2007). Previous research has demonstrated that athletes will only demonstrate their true performance in situations that are identical to the one's that they have developed their expertise within (Travassos, Araújo, et al., 2013). For example, an expert football player will only perform to their highest ability in ecologically valid environments that mirror the demands of football. Assessments that fail to adequately replicate the demands of the game will result in finding no performance differences between expert and non-expert performers (Pinder, Davids, Renshaw, & Araújo, 2011). Experiments that demonstrate expert superiority in only highly representative tasks are many. Farrow and Abernethy (2003) demonstrated that this expert superiority existed in tennis using expert and novice players in a tennis serve occlusion paradigm. The expert athletes' superiority in predicting the direction of the occluded serve was more apparent under a more natural condition (i.e. where athletes were required to physically move in the predicted direction of the tennis serve) compared to the unnatural condition (i.e. only a verbal predication of the service direction was required).

The second framework is the cognitive component approach, and directly opposes the theoretical paradigm of the first approach. This approach attempts to examine the relationship between fundamental cognitive and perceptual functions and athletic performance (Nougier, Stein, & Bonnel, 1991). In direct contrast to the expert performance approach, athletes have their general cognitive abilities measured by assessments that are purposely decontextualized from any sport specific material, removing entirely any ecological validity from the task. It is thought that the cognitive processes involved in making an athlete great also extends outside their domain-specific environment and can be demonstrated in various other conditions and tests (i.e. examining athletes on how they navigate through road traffic simulations or tracking various shapes moving randomly on a screen etc.). General functions such as cognitive flexibility, working memory, and inhibition are examined using computerised tests that present non-sport specific information to athletes (Voss, Kramer, Basak, Prakash, & Roberts, 2010). A further discussion on the cognitive component approach will be discussed in more detail in section 1.3, and a continuation of the expert performance approach will be reviewed.

1.2 Expert performance approach

In order to understand the expert performance approach in full, it is important to discuss the beginnings of this theory. The fundamental principles of the expert performance approach within a sporting domain -being that of measuring athletes in high ecologically valid environments- can be largely credited from the theories of how experts make intuitive decisions in all domains: heuristics and biases, and naturalistic decision-making. Both theories have been dedicated to measuring and explaining human intuition; albeit with opposing methodologies and conflicting assumptions (Kahneman & Klein, 2009). Nevertheless, an agreed upon understanding of what skilled intuition is, was provided by Simon (1992): "The situation has provided a cue: This cue has given the expert access to information stored in memory, and the information provides the answer. Intuition is nothing more and nothing less than recognition" (pg. 155). Decades worth of experiments shared between these two theories refined the argument proposing that many judgements and decisions come to one's mind that largely escaped the conscious awareness of what the evoking cues were in the environment. In turn, the arrival of many *in-situ* decisions can be considered automatic, involuntary and almost effortless (Kahneman & Klein, 2009). Examples of professionals using intuitive judgment can range from a firefighter commander that feels that the house is about to collapse, a nurse feeling that an individual is in grave danger and must act before the lab results come back, to a football player anticipating what the opposition is about to do with the ball before it happens. Professional intuition can be developed through prolonged engagement within a specific domain (Côté, Baker, Abernethy, Starkes, & Ericsson, 2003). This intuition helps the person make a decision despite being faced with high levels of uncertainty, time pressure, and high stakes.

In order to measure an expert's true decision-making capabilities that allows for intuitive processes to be used, there is one rule of thumb: An environment of high validity is a mandatory condition that permits skilled intuition to be used. In other words, the environment must provide similar cues to the individual that are reflective of the environment cues in which they learned in, triggering the onset of intuitive decision-making processes (Kahneman & Klein, 2009). If the environment does not provide sufficient representative cues, the simulated laboratory environment may be at risk of accidentally coercing athletes into using a more conscious system of decision making, to which is irregular for athletes that yield high levels of domain-specific expertise (van Maarseveen, Oudejans, Mann, & Savelsbergh, 2016). Accordingly, the large body of research that uses the expert performance approach has attempted to capture expertise in controlled laboratory settings with a high sense of realism of a natural environment. Many studies have also been dedicated into outlining the rules that sport-specific task environments must abide by in order to measure athletes in-situ, known as representative task design (Williams & Ericsson, 2005).

1.2.1 Representative task design

When measuring an athlete's domain-specific skill, it is important to consider three major concepts: First, the skills assessment needs to be valid and reliable (Franks, Paterson, & Goodman, 1986). Second, it is imperative to put the athlete through an assessment that incorporates as many representative characteristics of a realistic sporting environment as possible to allow for the expert's potential to emerge (Ericsson & Smith, 1991). Lastly, the design must ensure that it permits the athlete to demonstrate their skill rather than technique alone (Sunderland, Cooke, Milne, & Nevill, 2006). However, the ability to design an experimental task that evaluates a skill and encapsulates the essential task conditions and constraints in context is challenging (Williams & Ward, 2007).

The opportunity to replicate a situation and experimentally control the conditions is a fruitful area of research (Poplu, Baratgin, Mavromatis, & Ripoll, 2003). Hence, the majority of literature focusing on perceptual-cognitive skills in athletes have occurred in a laboratory-based settings using simulations of game-play (Lai et al., 2013). There has been numerous studies that have examined the aspects of the decision-making process based on what the next decision should be in a given situation (Belling, Suss, & Ward, 2015; Gorman, Abernethy, & Farrow, 2013; Helsen & Pauwels, 1993; Johnson & Raab, 2003; Vaeyens, Lenoir, Williams, Mazyn, & Philippaerts, 2007; Vaeyens, Lenoir, Williams, & Philippaerts, 2007). In these studies, participants adopted a perspective of a specific player on the screen as their own and are asked to carry out a physical movement or verbalize their intended response (see Figure 1). For example, 30 short clips of various football specific scenarios (i.e. 2vs.1, 3vs.2 and 5vs.3) were recorded and presented onto a 2D screen, with participants having to act as an attacking player on the field (Vaeyens, Lenoir, Williams, & Philippaerts, 2007). Simulations provide researchers with the ability to study the cognitive processes that underlie the process of a decision under controlled environments. The quality of the decision specific to the scenario is normally subjectively evaluated by a panel of experts to determine what the best decision would be. As a whole, these studies attempt to understand the underlying mechanisms of option generation, also known as the common expression ‘reading the play’ (Buszard, Farrow, & Kemp, 2013). Although the responses produced are generally limited to a few options and relatively simplistic to a skilled athlete, studies consistently have reported that experts made better and faster decisions more consistently and quicker compared to their novice counterparts (Travassos, Araújo, et al., 2013).

Despite many years invested in the area of experimental task design, the essential task condition characteristics and constraints expressed in sporting-performance contexts remains a constant struggle that researchers have yet to overcome (Williams & Ward, 2007). A protocol must be sensitive enough to not only capture the perceptual-cognitive elements that underlies a performer’s decision process, but also consider how a player’s behaviour interacts with different features of the environment (Davids & Araújo, 2010; Pinder, Renshaw, Headrick, & Davids, 2013). Accordingly, two major limitations are discussed when attempting to measure decision-making with simulation-based testing protocols.

Figure 1. A snapshot of the laboratory set up replicating the methodology of Vaeyens, Lenoir, Williams, and Philippaerts (2007) in Beavan and Fransen (2016).

One limitation is the potential lack of depth of conscious processing that simulations allow for. Simulations may not contain an adequate capacity permitting experts to display their deeper level of conscious processing during a situation as they would in a real game (Travassos, Araújo, et al., 2013). For instance, experts may continuously update their player profiles of individuals on the pitch during a game; potentially taking into consideration their teammates and opponents physical ability and fatigue levels during the match prior to executing their decisions (Dicks, Button, & Davids, 2010; MacMahon, McPherson, & Farrow, 2009). Additionally, experts may even reflect on the playing formation that the opposition's team is currently using and how it changed from the last half of even last time the two teams met (MacMahon et al., 2009). Interestingly, previous research has reported that a greater development of these in-depth tactical action plans and event profiles of players is associated with an increase in expertise (French & McPherson, 1999, 2004). Consequently, there may be a relationship associated with an increase in expertise and a decrease in the reliability of simulations used to test perceptual-cognitive skills.

A second limitation is that video-based decision-making tasks may undermine an expert's potential to emerge if the experimental conditions are not ecologically valid (Ericsson &

Smith, 1991). Two meta-analyses' were conducted investigating the perceptual-cognitive expertise in sport during different testing conditions. The first meta-analysis of 42 studies aiming to quantifying expertise difference in sport, reported that perceptual-cognitive strategies are task dependent; supporting the statement that sport-specific performance environments are necessary to ensure that the most ecologically valid criteria is met when assessing perceptual-cognitive skills (Mann et al., 2007). A second and more recent meta-analysis of 31 studies investigating decision-making among experts in sports provided crucial evidence supporting the observations of Mann et al. (2007), stating that stimulus presentation is a fundamental moderator of previously established expertise differences (Travassos, Araújo, et al., 2013). Results revealed that only in-situ conditions were able to consistently demonstrate an advantage of experts over novices compared to two-dimensional (2D) static and/or dynamic slide presentation. If 2D presentations are used, it may under-represent the visual-perceptual-movement responses elicited in game such as the exclusion of stereoscopic depth (i.e. depth perception) (Hohmann, Obelöer, Schlapkohl, & Raab, 2015); as human vision is three dimensional (3D). Perhaps, the use of 2D simulations cannot elicit true decision-making behaviour from the athlete because the task is not indicative of real performance (Araujo, Davids, & Hristovski, 2006; Farrow & Abernethy, 2003). Therefore, it is vital that enhancing stimulus presentation by using more realistic animations and environments should be a main consideration addressed in future research protocols.

Collectively, future experimental protocols must take into consideration the factors such as sport-specific environments and stimulus presentation to moderate the relationships between sporting expertise and perceptual-cognitive skills. Ecological validity cannot be provided with only few aspects of representative task designs, and an experimental protocol that has a few characteristics that nicely portray the real-world information does not immediately ensure more representative data (Vilar, Araújo, Davids, & Renshaw, 2012).

1.2.1.1 Representative task designs specific to football

Football is a team sport played by two teams consisting of 11 players on each team. The game is played on a grass or artificial turf ~110m by ~75m pitch (International Football

Association Board, 2017). All players are free to move anywhere on the pitch, resulting in a highly dynamic movement between players during both attacking and defensive phases of play throughout the game (Hewitt, Greenham, & Norton, 2016). The complexity that exists in sport let alone football is difficult to replicate in fabricated environments outside of a real match. Researchers aiming to mirror the demands of football are faced with a game that has no two situations are the same, with large amounts of uncertainty (i.e. opposition tactics), deception (i.e. athletes faking their intended direction of movement, or faking to shoot but continue to dribble) and unpredictability of ball movements (i.e. wind, pitch deterioration throughout the game, deflections off players etc.).

Despite these hurdles, many assessment tools have been developed to replicate the in-situ demands of football. In the age of technology, there are many new tools available on the market that propose the ability to measure the skill of an athlete by using large scale environments and expensive equipment in attempt to provide the athlete with higher sense of realism of a true in-game experience. However, despite these assessments being rare (i.e. only few clubs own them due to their price tag), the few in use have been largely made famous by the media and are portrayed as the ‘gold standards’ in the sporting community without having the scientific research to support such claims. Therefore, a short editorial was written in order to discuss these new assessment tools specific to a football domain, highlighting the importance of ensuring that the core elements that constitute representativeness task design are confirmed by researchers.

1.2.1.1.1 Editorial: Extraordinary tools require extraordinary evidence

This editorial has been accepted for publication. The full reference of the editorial is:
Beavan A. Extraordinary tools require extraordinary evidence. *Science and Medicine in Football.* 2019;3(4):263-4. https://doi.org/10.1080/24733938.2019.1678948

It is common practice to assess football players through a battery of tests covering all aspects of sporting performance. Practitioners may find the performance outcome measures valuable for athlete monitoring and talent identification purposes, while some scientists may have a further interest in investigating the underlying mechanisms that lead to better performance in those tests. Within these testing batteries, there are often assessments implemented to measure an athlete's sport-specific skill, as this is one of the relevant constructs for sport performance alongside tactical and physical performance.

When using any tool to measure an athlete's sport-specific skill, it is important to consider two major concepts: Is the assessment task reliable and does it hold various forms of validity (Franks et al., 1986)? First, it is important that the test is able to consistently measure what it is designed to measure, across multiple testing trials. Assessment tasks should not only be reproducible between players, but a player should be able to consistently demonstrate similar performances across several sessions to demonstrate its stability. Second, we also must ensure the test design will actually measure what it is designed to measure, known as construct validity. It is also imperative to put the athlete through an assessment task that incorporates as many representative characteristics of a realistic sporting environment as possible, known as ecological validity (Ericsson & Smith, 1991). Assessments that do not contain a high ecological validity may provide limited information towards the true athletic potential of each player (Phillips, Davids, Renshaw, & Portus, 2010). For instance, by definition, if an assessment task aims to measure the skill of an athlete, a decision-making component must be integrated in order to dictate how to act based on the opportunities available in the surrounding environment (Ali, 2011).

Currently, skill performance tests used in football testing batteries do not always contain both concepts. Talent identification programs generally use unique combinations of isolated tests such as ball control (Leyhr, Kelava, Raabe, & Höner, 2018) and dribbling (Aquino et al., 2016) to evaluate youth players' football performance (e. g. the Ghent Youth Soccer Project (Vaeyens et al., 2006)). Although it is important to know if an athlete is technically proficient, it is of greater importance to evaluate if the athlete can also execute this action in a timely-manner within a more game-realistic context. Many isolated assessments lack the ability to measure athletes' skill due to their lack of a decision-making component integrated in the task (Ali, 2011). If the dynamic nature of football is not represented in the design of these assessments, then they risk measuring variables that are not reflective of true performance in the sport. The Loughborough Soccer Passing Test is a great example of such principles. This football-specific assessment test was supported by multiple research papers on being a valid and reliable protocol that could distinguish players according to their playing level (i.e. elite vs. sub-elite) in young (Le Moal et al., 2014) and adult players (Ali et al., 2007). Yet despite this test being developed to assess short-distance passing ability under time pressure involving a decisional component, it was later discovered to not be representative of in-game passing ability (i.e. not ecologically valid) (Serpiello, Cox, Oppici, Hopkins, & Varley, 2017). Therefore, this nicely demonstrates that many football-specific protocols are based on a general understanding that the more an assessment looks like it has something to do with football, the more specific it is supposed to be of the demands of actual football (i.e. having high face-validity). Yet if the decision-making component is not strongly coupled with a sports specific action, true representative task design is missing (Dicks, Davids, & Button, 2009; Pinder et al., 2011).

Interestingly, the large expansion and investment in sports technology has given rise to many new and innovative assessment tools that may yield the potential to closely simulate how an athlete behaves in a game. These new assessment tasks may hold the capability to assess athletes also on their tactical, cognitive and physical abilities, all in one test. Examples of these new and currently used modern football-specific assessment tools are the Footbonaut (CGoal, Berlin, Germany), SoccerBot360 (Umbrella Software Development GmbH, Leipzig, Germany), Skills.Lab (Anton Paar SportsTech GmbH, Wundschuh, Austria), 360S Lab (INOV, Lisbon, Portugal) and ICON (Elite Skills Method, Navarra, Spain) amongst others. From these tests, a higher fidelity is achieved by immersing an athlete within a setting that attempts to closely mirror the interaction of the player and their game environment, aligning well with the improved ecological validity that skill assessment tasks must contain (Krause, Farrow, Reid, Buszard, & Pinder, 2018). Common traits across all the assessment tasks are visual displays of either abstract or realistic images coupled with auditory cues help to mimic the perceptual demands, whilst a large area of artificial grass combined with balls being dispensed with various degrees of spin, angle and speed all contribute in attempt to achieve a sense of realism.

These new-age assessment tools aim to improve on the aforementioned limitations with previous skill assessments, as they all contain a large perceptual-cognitive component to dictate action. Additionally, these tools may also help scientists to overcome the difficulty when attempting to assess an athlete's expertise in the most ecologically valid environment that replicates the unpredictable nature of the game, but with a methodology that is stable enough to be continuously replicated (Ali, 2011). Unfortunately, these new assessments also come with their own limitations. The designs of these tests come with a hefty price tag (i.e. the Footbonaut costs roughly 3.3$ million US dollars). However, it is our role as practitioners and scientists to exercise our due diligence to ensure that these new technological tools contain the crucial pillars of what constitutes a true assessment of a skill. We should not become anchored on the high price tags and flashy displays of technology; a ‘wow factor’ does not automatically ensure that the assessment tool is valid and reliable. This reputation comes from scientific evaluations of the assessment, and several studies are required to build up the required body of evidence to support the validity of each test (Impellizzeri & Marcora, 2009). Assessment that are not true representations of in game demands may also suffer from the same fate as the Loughborough Soccer Passing Test. To the author’s knowledge, only the Footbonaut amongst the assessments listed above has undergone scientific testing that has been reported in the scientific literature (Beavan et al., 2018). Therefore, as these tools are very rare and out of reach for the vast majority of clubs and researchers alike, we advocate for clubs with access to them to also grant external researchers access to use these assessments. Research can help to both improve our understanding of better representative assessment designs, but to also help evaluate the effectiveness of these assessment tasks, and whether they could yield the potential to be the gold standard of skills assessments in athletes.

End of editorial

1.3 Cognitive component skills approach

The second major approach to examine athletes’ cognitive abilities is the cognitive component skills approach, which studies the relationship between fundamental cognitive and perceptual functions and athletic performance (Nougier et al., 1991). In direct contrast to the expert performance approach, athletes have their general cognitive abilities measured by assessments that are decontextualized from any sport specific material, removing ecological validity from any task. All cognitive tests that are presented to athletes within this approach are domain-general, meaning that they are not sport-specific to an athlete’s domain. The overall aim of this approach is to understand how basic cognitive skill are linked to sporting performance (Voss et al., 2010). This approach states that athletes' expertise extends outside a sporting domain and can also be observed in assessments that are decontextualized from their respective sport altogether. For instance, it is believed that experts have superior cognitive abilities compared to lesser-skilled athletes and non-sporting populations, which can be measured using generic cognitive assessment tasks (Voss et al., 2010).

Evidence has been provided towards the theory that the demands of the sport also may improve the underlying mechanisms that support decision-making. For example, the ability of experts to concentrate on multiple people's movements whilst being able to detect unexpected objects appearing or multiple players' positions in the environment may be a ramification of being immersed in a team-sport environment; where tracking multiple players' movements in game is a norm (Memmert, 2006). Therefore, it seems reasonable to postulate that experts in team-sports should have an advantage in attentional capacity tests in comparison to lesser-skilled and/or non-team-sport athletes. This postulation was supported by Faubert (2013b) that tested a total of 308 individuals stratified into three distinct levels of sports performance (i.e. 102 professional players, 173 elite amateurs and 33 non-athlete university students) on a 3-dimensional multiple-object-tracking speed threshold task (3D-MOT). Results from the 3D-MOT revealed a clear distinction between the level of athletic performance and corresponding fundamental mental capacities such as attention for learning an abstract and demanding dynamic scene task. Adversely, Memmert, Simons, and Grimme (2009) reported no significant differences in basic attention tasks between expert team-sport athletes, athletes from non-team-sports or novice athletes. Although more research is needed to understand whether basic cognitive abilities are enhanced by playing sport, studies regarding the predictability of future performance on basic cognitive tasks based on the level of attainment in sport (i.e. experts vs. novices) on measures similar to the 3D-MOT would be an interesting avenue of future research.

Within the cognitive component approach, a sub discipline is to examine athletes' higher order cognitive functioning. These general, or 'core' cognitive abilities are formally known as Executive Functions (EFs), which refer to the family of top-down mental processes that subserve goal-directed behaviour (Miller & Cohen, 2001).

1.3.1 Introduction to executive functions

Throughout the cognitive maturation process into adulthood, children progressively improve their ability to use various sources of information to make decisions, stay on a task for longer, plan a future course of action and update their knowledge about a certain task from previous errors (Zelazo, Craik, & Booth, 2004). Interestingly, sport presents an ideal confirmation of these brain-behaviour developments. For instance, children playing team sports all chase after the ball together and have little concept or care for tactics, such as where the ball is versus where the ball might be in the future. This is aligned with children being described as impulsive, easily distracted and have little reasoning behind their decisions (Zelazo et al., 2004). However, as children get older, clear behavioural patterns begin to emerge. The ability to engage in goal-directed thought and action while negating acting on impulsive decisions can be attributed to the simultaneous development of cognitive control functions such as working memory, inhibition, and flexibility (Diamond & Lee, 2011). These three cognitive are known as the core EFs that forms the foundation from which other cognitive processes such as problem-solving, reasoning and planning are built upon (Diamond, 2013).

EFs are a consciously controlled process that engages in deliberate, goal-directed thought and action (Zelazo et al., 2004), and play a role in the decision-making process helping to resolve conflict especially in situations that are new (Best & Miller, 2010). EFs process the complexity of the presented situation, from both an external perspective that includes factors such as the number of stimuli to attend to plus the constraints (i.e. rules) of the environment and also the internal perspective such as overcoming the interference from habits and prior mistakes (Furley & Wood, 2016). The core cognitive abilities are especially relevant in demanding situations that require a fast and flexible adjustment of behaviour to the changing demands of the environment (Zelazo, Müller, Frye, & Marcovitch, 2003). Therefore, a person must be consciously aware of the situation and the decisions generated prior to carrying out an intended response. Hence, the intended response is not a product of an instinctual reaction created by non-conscious processes, but instead, an attentive decision. Collectively, EFs enable us to control our own thoughts and actions and experience a rapidly improved ability to gain control during the maturation process into adulthood.

1.3.1.1 Introduction to inhibition

Inhibition "is the suppression of covert responses in order to prevent incorrect responses" (VandenBos, 2007). Also known as inhibitory control, this EF refers to the ability to control attention, thought and behaviour in the presence of interfering both internal and external stimuli. It is also used to inhibit the dominant and automatic responses. For example, when a habitual response is not appropriate in a specific situation, then response inhibition is used in order to overcome and react more appropriately with a different action (Diamond, 2013). An example of how to measure response inhibition is using a Stop-Signal task. This task requires participants to respond to a stimulus by simply pushing a button in front of them, yet occasionally an auditory cue (i.e. the stop-signal) will sound alerting the participant to inhibit their ongoing or already initiated response to push the button (Congdon et al., 2012). Participants who have greater response inhibition would be able to stop their action to not push the button, and therefore make fewer errors.

1.3.1.2 Introduction to working memory

Working memory is the ability to differentiate between task relevant and irrelevant information, and to appropriately update the information being used to solve a problem by replacing no longer relevant information with new and more relevant information (Jewsbury, Bowden, & Strauss, 2015). Also known as updating, this ability is required to hold out-of-sight information in the mind, find new relationships between the retained elements, and work with it to achieve goals and meet task demands (Baddeley, 2000). One popular method to assess working memory is the use of object tracking tasks, involving keeping track of more than one moving stimulus in the scene for short durations (Lapierre, Cropper, & Howe, 2017). As previously demonstrated by Faubert (2013b) testing a total of 308 individuals stratified into three distinct levels of sports performance, players with better working memories are able to track objects more accurately and track objects at faster moving speeds.

1.3.1.3 Introduction to cognitive flexibility

Cognitive flexibly partially counts on both controlled attention and updating of working memory and is also known as set shifting. This ability defines one's ability to mentally shift from one task to another, utilizing alternative strategies, and processing more than one source of information (Zelazo et al., 2004). Set shifting is necessary for multitasking and for processing and managing several sources of information. It is usually measured by tests requiring switching between two timed tasks (Jewsbury et al., 2015). Cognitive flexibility has been commonly measured by the Wisconsin Card Sorting Test, where participants are asked to sort cards based on either the card's colour, shapes, number of figures, with the rule of sorting cards changing throughout the test (Lichtenstein, Erdodi, Rai, Mazur-Mosiewicz, & Flaro, 2018). People that can adapt better to the change of the sorting rule will in turn make fewer total errors.

1.3.1.4 The role of executive functions in sport

The explanation of how athletes are able to navigate and act within their environment using their perceptual-cognitive abilities matches closely with how previous researchers have described EFs are engaged within a sporting context (Jacobson & Matthaeus, 2014). For example, a football player is good at being adaptive to the ever-changing and unpredictable environment, such as switching between offensive and defensive roles (i.e. matching closely to the EF cognitive flexibility), processing the information relative to an extensive procedural and declarative knowledge base (i.e. working memory), and suppressing an intended action such as a pass if a player becomes marked by a defender, but also stopping a verbal response in situations such as a discussion with the referee or fan (i.e. inhibition). Often, the combination of these core and higher-order executive functions are described as 'game intelligence' in a sport specific domain (Stratton, 2004).

Furthermore, decision-making and problem solving – two concepts that athletes are expected to be used frequently during gameplay – has been linked strongly with EFs. Decision-making utilizes shifting, planning and categorization in order to choose between specific options in complex environments (Brand, Schiebener, Pertl, & Delazer, 2014), whereas problem solving relies on using higher order functioning such as reasoning and creative thinking in order to overcome difficulties and achieve a goal. Therefore, the seemingly logical association between EFs and decision making appears to have a high face validity for many researchers and practitioners, and the research interest in EFs from those involved with measuring and developing football performance is justified (Jacobson & Matthaeus, 2014).

Despite the relatively new interest in measuring EFs in a sporting population, previous research has made significant improvements in the understanding of their role in sport. A recent meta-analysis on nine studies that have investigated EFs in athletes reported that there is a statistically significant effect for high-performance level populations to perform better on assessments that measure EFs compared to lower-level and non-sporting populations (Scharfen & Memmert, 2019). More specifically, Verburgh, Scherder, van Lange, and Oosterlaan (2014) compared the EFs from highly talented junior football players to aged-matched amateur football players. The authors reported that using the performance results from EF tests could differentiate between the two groups with high accuracy (89%), inferring that elite populations yield better general cognitive abilities than lower-level athletes within the same sporting domain. Additionally, Vestberg and colleagues' recently extended their previous findings of the importance of EFs for success in football adults (Vestberg, Gustafson, Maurex, Ingvar, & Petrovic, 2012) to junior players (Vestberg, Reinebo, Maurex, Ingvar, & Petrovic, 2017), indicating that EFs are important continuously throughout the career of an athlete. Interestingly within these two studies, Vestberg and colleagues were the first to demonstrate the prognostic validity of EFs in sports, reporting that EF scores substantially predicted the number of goals and assists of attacking players two seasons later. The prognostic value of EFs specifically in football will be further discussed in section 1.3.2.5). On the other hand, additional research did not confirm the generalization of better EFs linked with expertise, where no discrepancies between different levels of expertise in tennis (Kida, Oda, & Matsumura, 2005), ice hockey (Lundgren, Högman, Näslund, & Parling, 2016), or basketball (Nakamoto & Mori, 2008) and additional football research (Jacobson & Matthaeus, 2014) were reported.

1.3.2 The relationship between executive functions and expertise

While there have been several research interests on the relationship between EFs and expertise in a sporting domain as mentioned in the previous section, there is a large paucity of knowledge on i) how EFs contributes to performance in sport, ii) what impact does EFs have throughout the process of expertise, iii) do experts require high-expressions of EFs in order to reach a high-level of attainment, iv) are EFs are important for success in sport, and v) is it therefore possible to predict future experts by measuring their EFs at young ages? These fundamental questions have been partially investigated in sport yet remains under-investigated to confirm the initial findings. Contrastingly, a large quantity of literature on the relationship between how other natural abilities (i.e. IQ, motor coordination etc.) contribute to the success of expertise in various competencies (i.e. business, academic achievement, music, and cooking, amongst many others) has been extensively explored in a broader scope of the literature. Therefore, large inferences can be made from this external literature from a sporting domain on the possible relationships between EFs and sporting success, and accordingly the non-sport specific research on the relationship between natural abilities and performance in several domains is discussed below.

The work from Françoys Gagné provides the perfect starting point for discussing the whether or not natural abilities can yield the capacity to be used as a prognostic tool to help discover a talented individual within a specific competency. His work, among notable others, provides beneficial insights into some fundamental questions like: What is talent in a specific domain? Can assessing natural abilities make inferences on how talented a person is at something or could become a talented individual in a specific domain?

In his earlier work (Gagné, 1999), Gagné first argued that the key terms *giftedness* and *talented* are independent terms to describe different concepts and should not be used interchangeably to describe a person's ability. With a model known as the Differentiated Model of Giftedness and Talent (DMGT) (Gagné, 1985), Gagné argued that a clear distinction between the two terms should be acknowledged and used throughout the literature more accurately. As sourced from Gagné (2004): "*Giftedness* designates the possession and use of untrained and spontaneously expressed natural abilities (called outstanding aptitudes or gifts), in at least one ability domain, to a degree that places an individual at least among the top 10 per cent of age peers… *Talent* designates the outstanding mastery of systematically developed abilities (or skills) and knowledge in at least one field of human activity to a degree that places an individual at least among the top 10 per cent of age peers who are or have been active in that field or fields." (Gagné, 2004, Pg. 120).

The mistaken interchangeability of talent and giftedness can be viewed from the common saying "hard work beats talent". This sentence is fundamentally wrong, as hard work allows an individual to become talented; whereas giftedness allows an individual to be have a natural born advantage to complete a task without having any more practice at such tasks than others. Therefore, perhaps the common saying should be "hard work beats giftedness".

Gagné's work relates mainly to how talent develops, and what role does natural abilities have on this talent development process. For instance, Gagné and colleagues have investigated how a person with an outstanding natural ability, such as high creativity or IQ abilities, transform this gift into a high-level skill that is used within a specific occupation. Moreover, other areas of interest have been what contribution does natural abilities have throughout the process of ageing, learning, training and practice? Lastly, what interactions do natural abilities have with the catalysts of performance (i.e. intrapersonal and environmental facilitators or inhibitors throughout the talent development process? By sourcing the answers to these questions form a non-sporting domain, their findings can help to set the foundations for future researchers within a sporting domain to have a prior understanding on the relationships that can be contingent towards EFs and sport.

1.3.2.1 Natural abilities

The DMGT displayed in Figure 2 displays the natural abilities that humans are born with on the left side. These natural abilities are predominantly hereditary-based abilities and can be already observed in children (Diamond, 2002). These abilities become useful and apparent through various tasks that children are confronted with in the course of their natural development with increased exposure to the world (Zelazo et al., 2004). For instance, a child's motor competence can be observed during engaging in sport or the interaction with the world and the many objects that surround the child. Social abilities allow children to interact with other children in the playground or at school. EFs can also be considered a natural ability that is hereditary dominated (Friedman et al., 2008). All children are born with natural abilities, however children who reach a level of outstanding expression of their natural abilities - being upwards of 10% within their population - hold the label of being ‘gifted’.

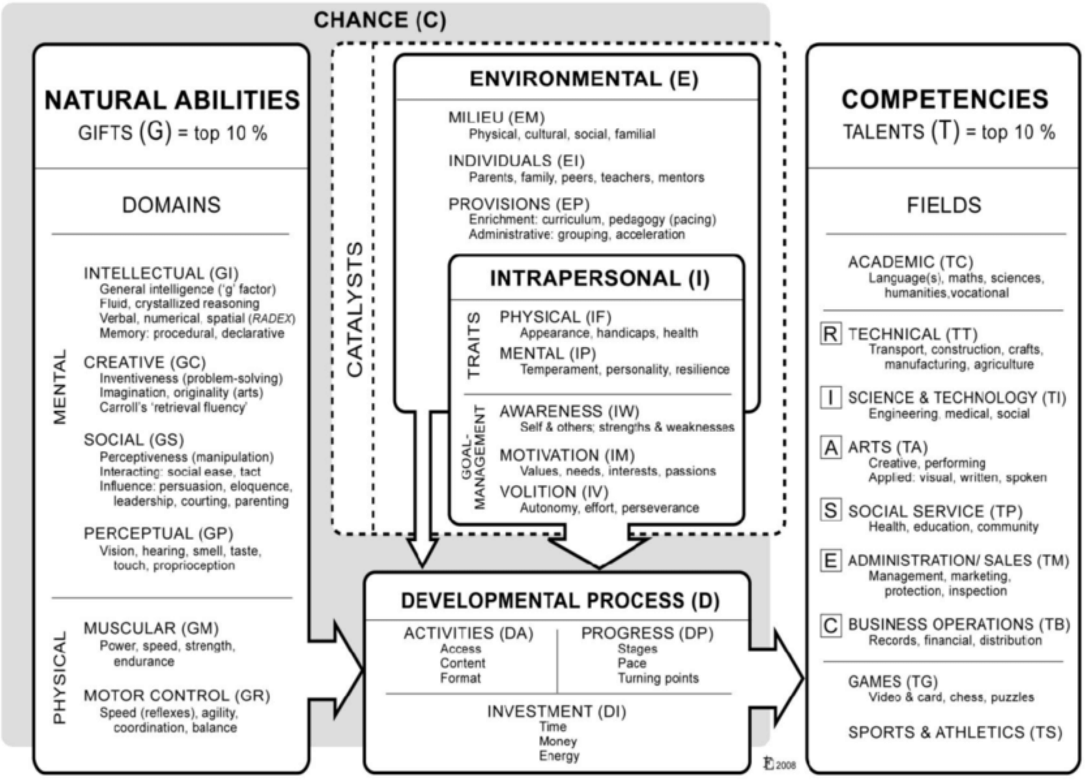


Figure 2. Gagné’s updated Differentiation Model of Giftedness and Talent (Gagné, 2004).

1.3.2.2 Systematically developed skills

On the right side of the model seen in Figure 2 are systematically developed skills. Talent is portrayed as developmental construct, meaning that dedicated practice is required to improve in such domain (Côté et al., 2003). All competencies require a unique set of skills that are required to be mastered in order to perform proficiently in the chosen field. This model demonstrates that natural abilities are the foundation upon which a competency rests upon, however in order to transform a natural ability into a well-trained skill of a particular field, practice is required (a counterpoint on this later is provided in more detail when the nature vs. nurture debate in section 2.1). Hence, competencies are an analogous term for systematically developed skills. Sporting expertise can be considered a competency, as learning how to play sport is developmental construct, practiced over many years of deliberate practice and deliberate play. Sporting skills, like other competencies are founded from an individual's natural abilities. In the case of many team sports, an athlete requires a high proficiency of motor competence in order to move in the environment, intellectual abilities such as EFs in order to plan and act accordingly based on the environmental constraints, creativity in order to think of new ways of scoring that the defenders will not anticipate, and social abilities during the interactions with teammates and coaches. However, the range of how competent the individual needs to be at in their domain is dependent on what level of performance the individual is demonstrating their skill in. Many individuals pursue the development of their skills at a slow pace, where engaging in sports is a weekend hobby that requires a minimum level of competence; whereas elite level athletes must yield the highest level of competence to perform. This may be why many studies have observed that higher-level athletes have better EFs than their lower-level counterparts (Huijgen et al., 2015; Vestberg et al., 2012; Vestberg et al., 2017; Voss et al., 2010).

Generally, performance assessments are used in order to provide normative values to compare an individual with a ranking of how their skills rank against others who have been learning for similar amounts of time. If the individual's skill is within the top 10% of their population within a specific domain, they are considered 'talented' according to the DMGT (Gagné, 2004). In a sporting domain, assessments of athletes' skills are very common in order to find the most talented players. Many teams hold multiple events each year that assesses not only their own athletes within their specific club or team, but also hold these events for athletes that are wanting to display their sport-specific skills in order to get acceptance into that club. Athletes are constantly compared to normative values on each aspect of skill. Yet this is not common outside of sport, only athletes are exposed to constant amounts of assessments that attempt to measure their domain-specific skills. For example, whilst individuals are practicing mastering their skill, individuals will be regularly assessed to track improvements, such as a piano examination each month or a dentist's end of year exams at university. However, outside of the small window of when individuals are enrolled in an institution or program where assessments are easily carried out/ part of the curriculum, performance assessments and performance rankings disappear. Subsequently, only subjective word of mouth or reviews found online are left rather any objective and standardize assessment or ranking on how one mechanic compares to another on a standardized assessment of their skills.

Interestingly, athletes in sport are a rare opportunity for scientists to measure the expression of their natural abilities at various time points of mastering their competency and analysing what contribution these natural abilities have on achieving expertise. There is a common belief that athletes are required to have an outstanding level of their natural abilities in order to develop into high-achieving athletes within their sport. In other words, being gifted is a mandatory prerequisite for becoming talented. For example, the Australian Institute of Sports tested the physical abilities of 8th and 9th grade students across many of the states. The students in the top 3% of their peers on any of the physical assessments were invited to a second round of physical testing. Once more, those who were amongst the top 10% of performers within the already high performing subgroup were once more invited to advanced training at the institute. At the end, having only the individuals that outperformed 99.5% of all adolescence tested on the physical performance measures remaining at the institute is a testament to some associations' beliefs that being gifted with high physical natural abilities is a prerequisite to develop into a talented athlete (Gagné, 2004).

This belief not only holds true for physical abilities in sport, but also for cognitive abilities across many other domains. One primary example of a cognitive measure that underlies academic success is IQ. A meta-analysis on almost 3000 studies that examined the factors that underlined academic success found that IQ was the leading factor averaging a correlation of 0.70 with academic achievement (Walberg,1984). As IQ is a natural ability that has such a strong relationship with success in many competencies, the link between high of cognitive abilities and performance in a chosen field is further reinforced. Therefore, the next section explores if using natural cognitive abilities can predict how successful an individual will be in their competency.

1.3.2.3 Can a natural ability predict future talent?

In order to understand whether natural abilities that are expressed at an early age (giftedness) could help to predict whether an individual would in turn become highly successful in their chosen competency (talented) requires a longitudinal approach. Apart from the study about predicting goals and assists two years post an EF assessment (Vestberg et al., 2012), there has been no longitudinal study conducted in sports on EFs and long-term success. Therefore, we once more have to draw interpretations from external research outside of a sporting domain in search of answers.

Remarkably, the longest ongoing study in psychology is known as the ‘Terman Studies of the Gifted’ (Terman, Baldwin, Bronson, & De Voss, 1926). Terman and colleagues first gathered a large cohort of gifted children between the ages of 3 to 12 years old, all of which were deemed to be gifted in their intellectual abilities, as they all had IQ scores of 140 and above. Intensive follow ups have persisted for over 80 years, and multiple research projects have analysed the data in many forms (Oden, 1968; Terman et al., 1926; Terman & Oden, 1947, 1959). One aspect of interest was the relationship between the children’s natural abilities and their success in their future competency. Reasonably, these children went on to hold some of the most outstanding positions in the domains of their choosing. This unique subgroup of the population successes was far above the average, with many children becoming politicians, a candidate for the American Superior Court, District attorneys, doctors, famed scientists, and held high rankings in universities, amongst many other prestigious positions and award winners (Terman & Oden, 1959).

Interestingly however, not all children attained such high roles in society. Terman mentioned that many of the members worked in more common roles such as working in trades, clerical positions, and uniformed personnel etc. These positions were deemed to be ‘mundane’ and do not hold the reputation of requiring a high level of intelligence to work in such positions. This finding led to Terman quoting: “At any rate, we have seen that intellect and achievement are far from perfectly correlated.” (Terman & Oden, 1947).

Thus, the relationship between natural abilities and developmental skills is weak and clouded by contextual factors. Despite the findings of longitudinal study demonstrating that many of the members within the gifted population had numerous achievements in society, it is difficult to attribute this solely to their IQ, and not the environment in which the individuals were raised in. The role that intelligence played cannot be singled out without accounting for the various levels of education that the children received, the value that their parents placed on education and initiative to achieve, and characteristics of personality (Oden, 1968). Furthermore, Baird (1985) describes the role of contextual factors that cannot normally be controlled for by science. There are an indescribable number of factors that may lead a person to attain the role that they chose in the future.

Life circumstances outside of people's academic attainment clouds the relationship between natural abilities even further, where Baird states:

"There are many stories of scientific discoveries that were dependent as much on accident as on the ability of the scientist. In many cases, accomplishment may be due to the right person being in the right place at the right time. Thus, given equally able and equally trained people, accomplishment may be dependent on the specific situations people find themselves in. In sum, people do so many things in so many contexts, that it may be unreasonable to expect academic ability to be highly related to attainment in every situation." (Baird, 1985).

1.3.2.4 Threshold effect of natural abilities

The final noteworthy conclusion from the collective findings from Baird (1985) and Terman's study of the gifted (Terman & Oden, 1959), is that although natural abilities are a prerequisite to competencies, the intensity that the natural ability must be expressed in the chosen competency appears to have a threshold of importance. This effect exhibits that there is a relationship between two elements until a certain threshold value, and above the value the relationship disappears, and the variables become independent; known as the 'threshold hypothesis'. Once the threshold is met, any expression of a natural ability past the minimal requirement has no further impact on performance. At this threshold point is where other factors come into play in order to improve performance.

Although Terman's intention was not to identify what the minimum threshold of IQ was required in order to achieve success in a competency, the findings of the study clearly portrayed the threshold hypothesis. More recent studies have begun to find the specific thresholds of IQ and performance in several domains. For instance, within creativity itself, Jauk, Benedek, Dunst, and Neubauer (2013) found that lower thresholds are required to produce one original idea (~86 IQ points), and a higher IQ was required (~120 IQ points) in order to produce a higher quantity of ideas, but higher IQ's did not produce a further quantity of ideas. Therefore, it appears that the minimum requirement of a natural ability is increased with the task difficulty, yet this relationship appears to be non-linear and requires many more future studies.

1.3.2.5 Can assessments of EFs be used predict talent in football?

In recent years, many researchers and practitioners have started to investigate what cognitive abilities may be important for a sporting domain, and whether youth athletes with similar cognitive profiles could be a new area to explore in talent identification strategies. The first attempt to demonstrate the potential predictive validity of EFs in football reported that the results of a cognitive flexibility known as the Design Fluency Test had a significant (p=0.006) correlation of 0.54 with the number of goals/assists the players had scored two seasons later (Vestberg et al., 2012). From this result, the authors stated that EF assessments can predict the future success in football players. However, ‘success’ in football is multifaceted, and a current limitation in the literature is the use of only including goals and assists as a measure of performance quality, which may overestimate the relationship between EFs and success in sport and rule out other playing positions (i.e. defenders). Subsequently, Verburgh, Scherder, et al. (2014) compared the EFs from highly talented junior football players to aged-matched amateur football players. The authors reported that using performance results from EF assessments could differentiate between the two groups with high accuracy (89%), inferring that elite populations yield better general cognitive abilities than lower level athletes within the same domain; and may be used as a prognostic tool for talent identification. Additionally, Sakamoto, Takeuchi, Ihara, Ligao, and Suzukawa (2018) assessed 383 male youth football players aged 8 to 11 years old on a series of EF assessments. The large cohort was applying for admission to an elite youth program of a Japanese Football League club. Interestingly, although the EF assessments were conducted within the battery of tests each player was assessed on, the data was not used to make an inference on whether a player was approved to join the program or rejected; whether a player was accepted or not was solely based on their in-game performance. This step allowed researchers to reduce sampling biases based on EF performance. Interestingly, the results showed measurable differences in EF performances amongst the selected and deselected academy players, being that the selected group had higher EFs compared to the non-selected group. Albeit, despite significant differences between groups was apparent, the small effect sizes and large variations in the data did not provide convincing evidence for the strength for EF assessments to differentiate between the groups.

Similarly, a large cohort (n = 700) of the American National Football League's (NFL) players during the Combine (where athletes are tested on all aspects of their performance with scouts present in attempt to play in the NFL) were tested on measures of their cognitive ability (Lyons, Hoffman, & Michel, 2009). The study reported the cognitive ability scores of athletes correlated near zero with their performance on the Combine and their success to reaching the NFL. In sum, the simplicity of attributing EF scores to future success may share the same fate that IQ has with academic achievement, where as long as athletes possess reasonable levels of EF, they have the capacity to play sport at a high level.

In sum, the current evidence across many domains of research appears to indicate that a certain level of EFs are needed to enter higher levels of playing (i.e. elite vs. sub-elite), however the results may not hold the predictive power to explain why some athletes reach the highest level of competition and those that do not. However, it can be argued that practitioners would be interested in knowing if including cognitive assessments in a talent identification battery to identify athletes that do not meet the cognitive requirements. Understanding whether an athlete who does not express high levels of cognitive abilities is still worth keeping in the squad or not would be valuable research outcome for practitioners.

Thus, the practitioner driven question of whether having low EFs or other perceptual-cognitive abilities is a problem that requires consideration in sport leads to the next key theme in this dissertation: the nature vs. nurture debate of EF development in athletes. Academies are great at identifying strengths and weaknesses in athletes and providing the necessary training and support in order to improve their performance in many areas. It is not yet clear if having low EFs is at all a weakness in athletes or having high levels of EFs is an advantage. On the contrary, if low cognitive abilities are identified, is it possible to improve EFs, or do athletes either have it or they don't?

1.3.2.5.1 Executive function development: Arguments for nature vs. nurture.

Gagné denotes that it is the natural maturation of the biological changes in brain growth (i.e. the central nervous system) that is the largest developmental agent to improving natural abilities. For example, changes in the brain structure is parallel to the development in cognitive achievements (Zelazo et al., 2004). This is also true for EFs, as previous genetic-based research in same-sex twin pairs found that the variance shared across EF domains was found to be 99% attributable to heritable genetic influences, with only trivial contributions (<1%) from environmental influences (Friedman et al., 2008).

Biological maturation indirectly affects the development of a skill, as the maturation of the central nervous system improves natural abilities, which in turn helps to improve performance (Gagné, 2004). However, as previously mentioned, talent is predominantly a developmental construct that is shaped from an individual's environment and practice. Improvements in a competency such as sport can be both formal and informal learning process. Formal learning provides a conscious intention needed to attain specific learning goals, known as deliberate practice (Ericsson, Hoffman, & Kozbelt, 2018). This type of learning is generally institutionally based, meaning that a developmental process is undertaken with the official recognition of the competency. These institutions can be thought of as going to school, driving classes, cooking classes, or joining a sports academy. On the other side is informal learning, which has is non-institutionalized formal learning, and can also be called 'deliberate play' (Berry, Abernethy, & Côté, 2008). Learning takes place with unstructured learning activities such as language skills being developed before reaching school, cooking at home, playing sport in a park with friends and so forth.

A current limitation in the sporting literature is that it remains difficult to confirm whether it is the natural biological maturation of the natural abilities or the institutional-based formal learning that contributes the most to the higher EFs demonstrated by higher-level athletes. In other words, is it the chronological age or the amount of playing time spent engaging in a sport of a player that is the main contributor to performance scores on tests of cognitive functions? This question currently remains unknown and under investigated is a sporting domain (Scharfen & Memmert, 2019). It is not yet known if being immersed in a high-level sporting environment facilitates EF development. A review from Colcombe and Kramer (2003) reported that longer durations of aerobic exercise produced more cognitive benefits compared with shorter exercise interventions in older adults. Opposingly, a more recent review by Diamond and Ling (2018) revisited the notion that various forms of exercise on their ability to enhance EFs, stating that new research after the initial review by Colcombe and Kramer (2003) has proved that this beneficial relationship more limited than previously stated. The review by Diamond and Ling (2018) reported that physical activity interventions have yet to show any meaningful benefits of exercise towards improving cognition, specifically related to improving EFs. Thus, it appears that the physical elements of sport do not contribute to EF development.

One possible explanation is that not all forms of physical activity are cognitively challenging, especially aerobic activity such as running on the treadmill or road cycling. One may argue that the ‘plainer’ exercises do not actively engage the brain to the same extent as team sports. Interestingly, although it may seem logical that activities with higher cognitive engagements and complexity would improve the brain, Diamond and Ling (2016) reported that this is not the case. Activities that are thought to be enriched with higher levels of cognitive and motor skill demands have conveyed only slightly better improvements towards EFs compared to activities that are relatively simple forms of exercise such as running on the treadmill. However, one major limitation that was reported in the Diamond and Ling (2016)’s review was that the ‘enriched activities’ that were ‘sport related interventions’ were in fact activities that were only in-part related to sport (i.e. basketball dribbling in a gymnasium); having the participants do sport skills in isolated situations rather than actually engaging in sporting games. To decompartmentalize sports is a major limitation, as the benefits from engaging in sport are thought to be due to the complexity of decision-making, uniqueness of each situation presented and having to perform these actions in time-pressured scenarios (Baker, Cote, & Abernethy, 2003); whereas doing repetitive exercises taken from a sport (i.e. dribbling a basketball around cones) and removed from its context highly removes many of the challenging elements of sport altogether.

Potentially, it is the activities within the sport training that engage EFs and therefore a possible dose-response relationship may still exist. Evidence of a dose-response relationship has been reported. Various forms of exercise (i.e. running games, jump rope, and modified football) coupled with longer interventions (i.e. 2 x 20 minutes/day) were more beneficial than shorter interventions (1 x 20 minutes/day) to improve EFs in participants (Davis et al., 2011). Similarly, game-based exercise once per week was related to better inhibitory control, and coordination training was associated with better working memory in junior (6-12 year old) tennis players (Ishihara, Sugasawa, Matsuda,

& Mizuno, 2017) compared to a control group. Moderate to large effect sizes (.34 to .42; $p = < 0.05$) of the reported dose-response relationships between cognitively engaging exercise (i.e. game-based exercise and coordination training) and EFs (i.e. inhibitory control and working memory) provided support for this premise (Ishihara, Sugasawa, Matsuda, & Mizuno, 2018). Additional research found that strategic sport athletes (i.e. adapting in highly varying situations including teammates, opponents, field position, and objects, such as football, ice-hockey, volleyball) were better able to adjust to the changing demands of the EF tasks compared to static sport athletes (i.e. self-paced situations in highly consistent and stable circumstances such as swimming, triathlon, gymnastics), which may be attributed to the differences in the cognitive demands of the sport (Krenn, Finkenzeller, Würth, & Amesberger, 2018). Furthermore, the number of hours spent in football-specific play activity during childhood was the strongest predictor of performance on tests of anticipation and decision-making and could differentiate between skilled and amateur groups (Roca, Williams, & Ford, 2012).

Diamond and Ling (2017) wrote another article on the effects of activity on brain functions, proposing that it might not be at all the actions or even the repetitive decision-making and cognitive engagement itself that are the underlying reasons for why EFs may be improved with sport, but rather the emotional investment that individuals feel when attending their sporting environment. Individuals that had the highest chance to improve their EFs were those that were experiencing four specific elements whilst engaging in an activity: 1) the environment must continuously challenge EFs in new ways, 2) the individual must feel a deep connection to the activity be emotional invested, 3) to have a mentor that believes in the efficacy of the activity, and 4) to seek pride, joy and self-confidence within the activity while reducing feelings of stress. In other words, it is the emotional investment that an individual has participating in football that may improve their EFs rather than the cognitive engagement towards making decisions and navigating within a complex and dynamic environment.

Nonetheless, if in fact it is the emotional component that is the main contributor to improving EFs, these four elements that have been proposed to improve EFs can still be directly applied to how athletes are interact within their sporting environments. Athletes, especially at the younger age groups, are constantly engaging in situations that are new, as it is unlikely that two sporting situations are the same in play. Team sport offers complex yet enjoyable exchanges with teammates as many academy programs believe that deliberate play within a players' youth is essential (Berry et al., 2008). Coaches, especially within structured academies, gives athletes a strong sense of leadership and mentoring in order to develop their skills. Therefore, it appears that team sports such as football are analogous with the four-element model required to improve EFs (Diamond & Ling, 2017).

In sum, the previous methodologies have not accounted for many elements that may improve EFs. Thus, whether engaging in true gameplay rather than any simulation or isolated sporting actions better facilitates EFs still remains unknown. Interestingly, there is a large amount of research that may help to explain whether it is possible to transfer the benefits of engaging in sport-specific activities to the brain, or whether engaging in only cognitive-based training can transfer into sporting abilities.

1.3.2.5.2 Cognitive Skill Transfer

Under the umbrella of the nature vs. nurture debate, a simultaneous debate is ongoing whether training on a cognitive task can improve performance on an unrelated and untrained cognitive task, known as the cognitive skills transfer hypothesis. Researchers have long debated how much of a transfer is possible into a different domain; it is likely dependent on the extent of differences between the two tasks (Barnett & Ceci, 2002). This is relevant for understanding whether the engagement from sporting activities could in theory improve general cognitive abilities and vice versa. This debate has been heavily researched, tracing back to the theories that are more than a century old: a) the formal discipline theory and b) the transfer by identical elements theory. Both theories are based on the idea that a transfer depends on the similarity between the content that was learned and its application within a different context.

There are two spectrums within the cognitive skill transfer hypothesis, known as *'near'* and *'far'* transfer; also commonly reported as 'narrow and broad' transfer. Near transfer proposes that an induvial with a specific expertise in a particular field will only demonstrate superior performance within their specific environment, and these cognitive abilities do not extend outside of their domain of expertise (Harris, Wilson, & Vine, 2018). Near transfer is restricted to occur between two tasks that are very similar contexts or variation. For example, playing futsal in order to improve the technical proficiency for playing football. This type of transfer is heavily supported with the expert performance approach, as explained in the beginning of the introduction, section 1.2.

One of the first studies to explore the concept of transfer within a sporting domain was done in chess by Edward Lasker in the 1940's, a chess grandmaster himself. Lasker discussed the contrasting abilities of the average working memory capacity being limited to between 5-9 items; whereas a chess grandmaster can play blindfolded against multiple opponents at the same time, requiring the grandmaster to memorise hundreds or thousands of potential moves. However, Lasker examined the memory of a dozen chess grandmasters and mentions that a grandmaster's memory is only exceptional when it is tested in relation to a chessboard. Further studies continued to use chess players to access their abilities on chess-specific and unspecific assessments. De Groot (1965) later found that chess players had an extraordinary ability to remember chess patterns and found that this ability increased alongside expertise. Specifically, as chess grandmasters' working memory capacity is greater than that of the average chess players, working memory was deemed to be important for chess. However, Chase & Simon (1973) followed up on this research, finding that chess players also were found to have a profound ability when it comes to chess pieces, but results of their working memory capacity in non-chess related assessments were normal compared to the normal population. For example, chess Grandmasters' ability to recall chess pieces that were positioned randomly on a board was only substantially better than that of amateur players (Chase & Simon, 1973). The specificity of chess players' memory has been nicely demonstrated in the everyday life of Magnus Carlsen, the current World Chess Champion. Magnus was recently asked if he considers his memory to be extraordinary, replying:

"No, I forget all kinds of stuff. I mean, I'm pretty good at remembering names, but I can never remember faces. I regularly lose my credit cards, my mobile phone, keys and so on" (Levitin, 2014).

Opposingly, the far transfer hypothesis states that prolonged experience in activities such as sports and video gaming can improve the individual's cognitive abilities that underly their expertise (Voss et al., 2010). These adaptations in general cognitive abilities, such as EFs, has been thought to be the reason that higher level athletes outperform their lower-skilled and non-athletic counterparts on assessments that are independent of a sporting context (Furley & Memmert, 2011). A far transfer is between two seemingly related, but quite distinct contexts or variations. For example, attempting to transfer the effects of an object tracking task on a computer into helping players track players on the field during gameplay. This theory is strongly supported by the cognitive component approach discussed in 1.3.

Research has provided many mixed findings on whether a far transfer exists is possible in sporting applications, but there are new and robust studies in support that transfers are possible. For example, Krenn et al. (2018) investigated the EFs profiles using a large cohort of elite level athletes (n=184) competing in various sports at the highest level of international competitions (i.e. Olympic Games, World Championships or European Championships). Athletes were classified as belonging into one of three sporting groups: 1) Static sports were deemed to be self-paced situations with consistent and stable circumstances, including swimming, archery, and athletics amongst others. 2) Interceptive sports were classified as sports that require a higher dynamical coordination between the body parts and an implement or object in the environment. Sports that are under this term included combat sports, badminton and tennis, amongst others. 3) Strategic sports were classified as sports that require the athlete to adapt to the dynamic environment with highly varying situations caused by teammates, opponents, field position and objects in the environment. Sports meeting this criterion are beach volleyball, ice hockey, sailing, amongst others. This study demonstrated that athletes from strategic sports had better ability to mentally shift between opposing response reactions, and flexibly adjust to the changing task demands, compared to athletes within interceptive sports, but not meaningfully different between interceptive sports. Having a higher working memory capacity is in line with the cognitive demands of strategic sporting environments, with strategic sport athletes needed to hold and update information in their mind while negating unimportant information (Jacobson & Matthaeus, 2014); whilst this may not be as important in sports with lesser cognitive demands such as swimming and marathon running. This study provided supportive evidence to say that athletes in more cognitive demanding sports outperformed athletes in sports with low cognitive demands, in some measures of cognition, emphasizing that the different EF profiles may have been transferred from engaging in the sport itself.

Despite some recent findings in support of a far transfer (Voss et al., 2010), there is little evidence to support that a transfer exists between improved cognitive abilities directly related to engaging in sport specific activities. Even the findings from Krenn et al., (2018) found that, although some measures of cognitive abilities were different, there were many other measures that observed no meaningful differences in EF tasks between the static, interceptive or strategic groups; hindering the generalizability of improved cognitive abilities as a result of being immersed in specific sports even with a population group of athletes performing at the highest levels of competition. Furthermore, a large review focusing on the notion of 'brain-training' programs being able to transfer to sporting performance (resting on the theoretical foundations of far transfer existing) argued that no substantial or consistent body of evidence exists in support of improved cognitive capacities that can be attributed engaging in professional performances (Simons et al., 2016). Furthermore, a more recent meta-analysis of 43 studies examining the transfer effects of cognitive training core cognitive functions on skills such as attention and decision-making concluded that limited evidence that improvements found in lab-based cognitive tasks transfer to real world benefits, including sport. Therefore, there is a vast amount of research against the notion that far transfer is possible between training cognitive abilities and sporting performance independently but expecting for a beneficial transfer between them.

Lastly, the DMGT model from Gagné demonstrates that although natural abilities are a part of the foundation that a competency is built upon, there has been no evidence to support that a transfer exists between these two constructs (Gagné, 2004).

1.3.2.6 Development of executive functions in youth athletes

One fruitful and unexplored avenue that would largely contribute towards the born vs. made debate is to explore how youth athletes' EF develop across periods of maturation. Examining whether the developmental trajectories of EFs differs in any way between athletic population compared to non-athletic populations has merit. Being exposed to a high-performance football environment yields the potential to best improve EFs by the aforementioned criteria set by previous research i) all four elements can exist stated by Diamond and Ling (2016), ii) continuously challenges the athlete in novel situations that are highly demanding, iii) practice and gameplay abides by the dose-response relationship that exists for many sessions over the week that are ≥ 90 minutes in duration (note: 40 minutes longer than (Davis et al., 2011)) and iv) ≥ 1 session a week, which was demonstrated to show enough activity to facilitate EFs in children between 6-12 years old (Ishihara et al., 2017).

In the general populations, individual EFs follows different developmental trajectories, but collectively they are fully developed between the mid-adolescent and adult phase (Anderson, 2002). Research also demonstrates that EFs develop in an inverted U-shaped trajectory across the lifespan of participants, where specifically around reaching adulthood (i.e. ~25 years old) is where decrements in performance are observed. This decrement in EF performance progressively becomes worse with age (Dempster, 1992; Mayr, Spieler, & Kliegl, 2001; McDowd & Shaw, 2000). However, if the reported benefits that a high-performance team sport athlete is exposed to are true, then there should be three clear findings. The first main observation can be made cross-sectionally. If the importance of EFs to compete at a higher-level is true, then there should be a refinement of athletes that display the best levels of EFs as age progresses. For example, the adult professional players should display better EFs compared to their younger academy counterparts, displaying that players with more experience playing sport have higher EFs, but also that players who lack adequate EFs cannot keep up with the mental pace of the game and in-turn would not continuously be kept within the academy throughout the years prior to reaching the adult level. Some research is in support of this, reporting that highly talented youth football players have a superior ability to suppress ongoing motor responses compared to their less-talented and normal population group counterparts (Verburgh, Scherder, et al., 2014). However whether this is consistent across increasing age group is inconsistent, as a high variation of participants' age distribution across additional age-related studies in sport may have skewed the results in youth athletes (Vestberg et al., 2017), and it remains unknown how much EF change between distinctive age groups in adolescent team sport players.

The second main observation can be made longitudinally. If engaging in sport-specific activity improves EFs, then athletes should not suffer from the same cognitive decline patterns observed in general populations. Instead, playing sport should be a strong enough stimulus to delay the effects of cognitive decline, and longitudinal analyses could even display that older athletes are still improving their EFs. Mapping out the longitudinal development of EFs in football athletes is largely beneficial to understanding whether these assessments could contribute towards talent identification. Without longitudinal data, it is difficult to confirm whether a player with a lower EF score can also be considered less talented (i.e. has a lower likelihood of reaching elite levels of football performance).

Lastly, if a possible dose-response relationship may exist between the amount of time engaging in sport-related activity and improved EF, this relationship may also extend into observable position-specific differences within the same sport, as the in-game demands placed on a goalkeeper are very different from those placed on midfielders (Saygin, Goral, & Ceylan, 2016), and this may exacerbate differences in EF over time. Scharfen and Memmert (2019) put forth the idea that factoring in playing positions may potentially improve the predicted development curves of athletes. Currently, little is known about the dose-response relationship of EF and sport, and whether different playing positions has a strong enough effect to change specific EF has yet to be determined.

Overall, understanding whether EFs can be developed through engaging in sport and further used as a prognostic tool to scout for future talent are both questions that are relevant to sporting clubs. As these protocols are already being used in sporting clubs by practitioners, scientists can help to confirm or negate the suitability of using EFs in a performance diagnostic battery. Therefore, a preliminary investigation into the role of EFs in sport was first undertaken to confirm whether there was any rational in further investigating the nature vs. nurture debate, which would require a considerable amount of resources and time.

The full reference for the preliminary investigation can be found in the appendices section 8.1: Preliminary study: Age-Related Differences in Executive Functions Within High-Level Youth Soccer Players.

1.3.2.6.1 Preliminary investigation into executive functions: part 1

It may be speculated that the vast majority of stimuli which athletes are exposed to are hidden within the sporting environment, as it is impossible to consciously attend to every stimulus. Many stimuli may go unnoticed during a game that may non-consciously change and/or challenge the athlete's sporting performance (Kibele, 2006). Interestingly, to the author's knowledge, no EF battery of tests has previously incorporated an assessment that measures the influence of non-consciously perceived stimuli on any performance outcome such as response speed. All EF assessments have previously used very explicit forms of stimuli within their tests, which underrepresents the importance of understanding the influence of information that largely escapes human consciousness. Therefore, the introduction of a new EF test that measures the impact that nonconsciously (implicitly) perceived visual cues has value. The development and further rational of using an implicit response time task can be found in the appendix, section 8.1. Accordingly, a core part of the study aimed to examine the influence of an implicit precue on response times in a precued response time task, as measuring implicit response processes compared to explicit measures may be more appropriate to sports where fast and accurate responses are required.

1.3.2.6.2 Preliminary investigation into executive functions: part 2

Previous research has left an insufficient body of evidence to conclusively describe the relationship between EFs and sporting performance for football players. As such, the next logical step to furthering our understanding of the contribution of EFs is to in greater detail examine the relationship between age and EFs in more distinct age groups (i.e. 12-year old's compared with 13-year old's etc.) within players who are in a structured sporting environment. Previous methodologies have used a relatively high variation of participants' age distribution within each group. For example, Vestberg et al. (2017) grouped players age ranging from 12-19 years together, and it has not yet been investigated whether more specific age-group (i.e. stratified by distinctive birth years) differences are revealed in a homogenous population of high-level athletes. EF are still developing rapidly during the adolescent phase (Li et al., 2004). However, Gagné noted that an essential requirement to assess an individual's natural abilities is using specific ages, and to not cloud the development of a natural ability with various time points of maturation and attribute them to factors such as time spent completing a certain competency. In course of normal aging, early adolescents experience an increased effectiveness to engage in deliberate, goal-orientated thought and action, and these changes are have been reported to be significantly improved between children and young adults (Zelazo et al., 2004). Therefore, as natural abilities have strong developmental curves during the maturation process prior to adulthood, the comparison of between groups must be made with the same age individuals. Therefore, the second aim of the preliminary investigation was to investigate age-group differences on EF tests in a homogenous population of talented youth football players.

In summary, the preliminary study demonstrated that older football players (i.e. U17-U19's) performed significantly better on EF tests compared to their younger counterparts (U12-U13's) in a highly talented population. In fact, significant group by performance interaction effects were observed for each test. As noticeable improvements in EF performance were observed with an increase of one year in age and playing experience during early adolescence, future studies should take caution when grouping players together with multiple birth years, especially in younger populations where the magnitude of change between ages are more prominent.

The present study provided merit for the inclusion of the implicit stimuli response time task, demonstrating that implicit stimuli can either enhance or hinder motor behaviour in highly talented youth football players based off the congruency of the delivered precue. Choice reaction time tasks are common in to assess reaction times, but only using explicit information. Therefore, the results from this implicit test could further our understanding of how athletes are able to act upon both implicit and explicit sources of visual information and in the future should be compared with additional populations. Lastly, as previously stated, this the topic of EFs in sport is largely practitioner driven question. Seemingly, the last aim of the study was to develop an overall EF sum score, allowing practitioners to more easily interpret and convey the results of tests to coaches and players alike. Although the EF sum score equation provided within the current study is unique to the battery of tests that were used, it demonstrated that a sum score can be used to differentiate between age groups.

This study presents important findings for researchers and practitioners alike and confirmed that age-group comparisons of EFs could be perceived as important. However, a small caveat was that the preliminary study was not able to demonstrate the major effects of age or experience that the previous researchers reported, stated throughout this Chapter. Therefore, a decision to continue the investigation of the role that EFs play in football was supported. Follow up studies would however require a more in-depth analysis of the potential independent effects such as field position, more detailed playing experience forms and the inclusion of more age groups are needed to form a focus of future research on the role of EF in football.

Chapter 2: Statement of Problems and Research Aims

While there have been several research interests on the relationship between EFs and expertise in a sporting domain, much of the knowledge of this relationship is sourced from literature that is external to sport. Unanswered questions of how EFs develops longitudinally in athletes and how natural abilities contributes to playing sport remains widely unknown. Therefore, to advance this field of research within a sporting domain, a systematic approach to the implementation of assessment tools is needed. Furthermore, the creation of new cognitive and perceptual assessment tools can be a beneficial addition in order to assess athletes with varying levels of perceptual information or action fidelity.

2.1 Contributors to executive functions development in athletic populations: Nature or Nurture?

Research has yet to establish a clear understanding of what factors are contributing towards why higher-level athletes have been shown to yield higher levels of cognitive functioning compared to lower level athletes. Comparing the contributions that age, years of experience playing football and playing position on the developments of EFs would contribute significantly towards the nature vs. nurture debate. Additionally, it remains unknown if there are factors associated to high-level football training that may influence age-related changes or are such trajectories merely a reflection of the normal maturation of the central nervous system. For instance, it is not yet known if being immersed for an extensive period of time in high-level sporting environments has a positive influence on EF, which may alter high-level athletes’ development curves compared to populations who are not exposed to these environments.

Furthermore, many studies in domains outside of sport have consistently reported that it is likely that a certain level of a natural ability such as intelligence (i.e. IQ) is required to enter a certain field, but any further expression of intelligence was not related to improved accomplishment in the occupation, known as the “threshold” hypothesis. The variability in expression of the natural ability that extends past the threshold of necessary expression is achieved does not strengthen the relationship with improved performance in the chosen competency. Therefore, understanding whether EFs (being a natural ability) that is used as a predictor of future sporting success (being a competency) also suffers from the threshold effect has merit. In other words, is there any evidence to support that players only need a certain ‘amount’ of EFs in order to play football at a high level?

Aim 1: To examine whether chronological age (representing nature), years of experience playing football and playing position (together representing nurture) influence the developmental curves of EFs in a large homogenous population of high-level football players.

2.2 Introducing a new football-specific skills assessment

Football is a dynamic sport that requires players to utilise a highly automatic yet complex cohesion of physical fitness, football-specific motor skill, and perceptual-cognitive skill. Many attempts have been made to capture football performance as a whole in one specific test, allowing an all-encompassing test that would eliminate the need to assess athletes on multiple skill tests in isolation of each other. However, previous tests have fallen short of being able to replicate the real demands of football, leaving athletes being tested in a tool that does not have the capacity to demonstrate their expert potential. Consequently, new technological advancements are required to design skill assessments that have the necessary perceptual-action components to help mirror the natural environment that an athlete experiences during a match. Practitioners and scientists alike also depend on the results of an assessment task to be a meaningful and a true representation of performance, which is able to differentiate between athletes’ skill levels. Notably, on many occasions, tools have been purchased and implemented in practice without first measuring their true effectiveness, leaving some practitioners with a blind trust in their assessments. Therefore, as a new football specific skills assessment, known as the Footbonaut, is a fundamental assessment tool throughout several studies of the current dissertation. a necessary prerequisite is to first assess the validity and reproducibility of this tool in a football population.

Aim 1: To assess the test-retest reliability of the Footbonaut.

Aim 2: To assess its discriminant validity by investigating the influence of age and football experience on test performance.

2.3 Are executive function assessments appropriate within a football domain?

Longitudinal studies in athletic populations are lacking, limiting the generalizability of existing longitudinal EFs studies from general to athletic populations. Longitudinal studies that map out the developmental trajectories of high-level athletes' EFs allow for inferences to be made on the practical validity of using EFs as a prognostic tool for talent; as the validity of this concept has yet to be addressed in the literature. Overreaching conclusions on the validity of EF assessments to help predict talent rests upon the weak body of evidence sourced from cross-sectional data, small sample sizes and underpowered statistical approaches. However, this knowledge has already inspired practitioners to begin implementing these tools without the required scientific literature to support such practices. In sum, investigating whether EFs could help practitioners make more informed inferences on young athletes' future performance potential is valuable, or to understand whether the emphasis that is currently being placed on high natural abilities being a pre-requisite for talent is justified or not.

In the following study, Bayesian statistics are used in order to measure the longitudinal development of both domain-generic and domain-specific cognitive abilities. Bayesian statistics were chosen as a clear progression towards analysing data, learning from the previous studies results conducted within this dissertation to directly incorporate this newly updated knowledge of EF growth patterns into the longitudinal analysis within Chapter 5. For example, priori information concerning the domain-specific and domain-generic relationships with age and experience was obtained in Chapter 3 and 4 in order to make more accurate inferences on the longitudinal development of EFs throughout late childhood into young adulthood.

Aim 1: To document age-related changes in both relatively domain-specific (i.e. assessments that present either football specific information or require football-specific action) and relatively domain-generic (i.e. assessments that neither represent football-specific information nor require football-specific action) abilities in a longitudinal manner.

Aim 2: Evaluate the practical validity of using measures of EFs as a prognostic tool for identifying talented players in youth football.

2.4 Improving the task design of the Footbonaut

Following on from the studies contained in Chapters 4 and 5 the skills assessment task known as the Footbonaut, may have been under-represented the actual perceptual-action domains that players are subjected to in a football match. Albeit, the Footbonaut holds many strengths, such as its standardized protocols, with a football related action, and can still be used in alternative ways to continue to analyse athletes under the expert performance approach discussed in Chapter 1. Therefore, the principal aim of the following studies is to not fall into the textbook example of creative destruction, where older technologies are simply discarded and replaced with new tools on the market rather than attempting to improve the tools currently in possession of the club.

2.4.1 Study A) Implementing stroboscopic glasses

Vision is a fundamental source of afferent feedback during the execution of gross motor skills (Winnick, 1985). When motor skills become more complex and the surrounding environment becomes more dynamic (i.e. changes in information flow that occur during the execution of a motor skill), optimal use of visual information increases (Houwen, Visscher, Hartman, & Lemmink, 2007). A previous study by Fransen et al (2017) used the stroboscopic glasses on youth athletes while dribbling around a course of cones. However, football is a largely dynamic skill sport where external stimuli dictate the formulation and execution of a skill. Dribbling a ball around pre-set cones is a closed skill (i.e. predictable and self-paced) and may not be representative of dribbling during a game, which is an open skill. Thus, it remains unknown how restricted visual feedback affects other aspects of football-specific skill performance, particularly in tasks that encompass a perception-action coupling that is more representative of football game play.

Aim 1: To investigate how restricted visual feedback impacts the performance in a football-specific skill assessment that requires a more complex and reactive perception-action coupling.

2.4.2 Study B) Implementing inertial measurement units

New advancements in inertial measurement unit sensor technology have unlocked the ability for researchers to objectively measure the movements of the head of an athlete, understanding how athletes explore their environment. The recent interest in how athletes move their head, known as visual exploratory actions (VEA) has provided valuable insight into the relationship between VEA and performance with the ball. In previous research, a higher frequency of VEA (i.e. a higher amount of visual scanning) before receiving the ball was related to improved performance with the ball. Players who explored their surroundings more before receiving the ball lead to faster pass responses, more attacking passes, more passes to a different area of the field, and more turns with the ball McGuckian et al. (2019). Therefore, this sensor technology was introduced in the Footbonaut in order to explain the underlying perceptual abilities that contribute to better performance between various age-groups.

Aim 1: To investigate the influence of visual exploratory action variables on passing performance in a football-specific skills assessment.

Chapter 3: The Rise and Fall of Executive Functions in High-Level Football Players

The content has been reformatted for the purposes of this thesis. The full reference details of the published manuscript are:

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

3.1 Abstract

Introduction: Executive functions are higher-level cognitive functions. Despite being relevant to many aspects of everyday life, it is contentious whether executive functions are important for high performing athletes. Executive functions increase throughout the career of an athlete, yet it remains unknown what are the main contributors. Therefore, this study examined the effect of age and experience on executive functions in a cohort of high performing football players. **Methods:** Data were collected over three seasons, resulting in a mixed longitudinal sample of 1018 observations in 343 male players (1-5 observations/player, age: 10.34 – 34.72 years; playing experience: 5 – 22 years) from the U12-Senior age groups of a professional German football club. Players participated in four cognitive tasks aimed at measuring higher-level cognitive functioning: a precued choice reaction-time task, a stop-signal reaction-time task, a sustained attention task, and a multiple-object tracking task, from which a total of eight dependent variables related to response time and/or accuracy were derived. **Results:** Linear and non-linear mixed effects regressions were used to investigate the relationship between age, experience and executive functions. A second order polynomial revealed that, generally, a negatively accelerated curve best described the relationship between age, experience and executive functions. An increasingly smaller difference in executive functioning was generally observed between subsequent age groups, with a performance plateau evident around adulthood (~21 years old). Age and experience only explained a very low to moderate proportion of the variance in executive functions (marginal explained variance ranged between 2 and 57%). A significant age by field position interaction effect was only observed for the sustained attention task's accuracy and response time components ($p<0.001$). **Conclusions:** Both age and experience showed a negatively accelerated relationship with executive functions in youth football players, and this relationship was generally field position independent. These negatively accelerated curves seem to reflect those observed in general populations, where a plateau phase in the development of higher-level cognitive functioning is also observed around 21 years, reflecting the maturation of the central nervous system in normally developing individuals. Therefore, this study challenges the assumption surrounding the use and validity of executive functions as a measure of football performance potential in high performing athletes.

Keywords: Cognitive, athletes, academy, soccer, threshold effect

3.2 Introduction

For many years now, there has been a large interest in exploring the relationship between sporting expertise and general cognitive abilities, known as the cognitive component skill approach (Nougier et al., 1991). This approach states that athletes' expertise extends outside a sporting domain and can also be observed in assessments that are decontextualized from their respective sport altogether. For instance, the cognitive component approach states that experts have superior cognitive abilities compared to lesser-skilled athletes and non-sporting populations, which can be measured using generic cognitive assessment tasks (Voss et al., 2010). One area within this approach that has gained recent popularity is measuring executive functions (EF). Executive functions refer to the family of top-down mental processes that subserve goal-directed behaviour (Miller & Cohen, 2001). There is a general agreement in cognitive psychology that the three core EFs are: inhibition, working memory and cognitive flexibility (Diamond, 2013). These core EFs are a subcategory of cognitive functioning and form the base to which higher-order EFs are built upon, such as reasoning, problem solving and planning. Executive functions are especially relevant in demanding situations that require a fast and flexible adjustment of behaviour to the changing demands of the environment (Zelazo et al., 2003). Therefore, a person must be consciously aware of the situation and the decisions generated prior to carrying out an intended response. Hence, the intended response is not a product of an instinctual reaction created by non-conscious processes, but instead, an attentive decision.

The explanation of how athletes are able to navigate and act within their environment using their perceptual-cognitive abilities matches closely with how previous researchers have described EFs being used within a sporting context (Jacobson & Matthaeus, 2014). For example, a football player is good at being adaptive to the ever-changing and unpredictable environment, such as switching between offensive and defensive roles (i.e. matching closely to the EF cognitive flexibility), processing the information relative to an extensive procedural and declarative knowledge base (i.e. working memory), and suppressing an intended action such as a pass if a player becomes marked by a defender, but also stopping a verbal response in situations such as a discussion with the referee or fan (i.e. response inhibition). Therefore, the seemingly logical association between EFs and decision making appears to have a high face validity for many researchers and practitioners, and the research interest in EFs from those involved with measuring and developing football performance appears warranted.

Justifying their face validity, a recent meta-analysis on nine studies that have investigated EFs in athletes reported that high-performing athletes possess better EFs compared to lower-level and non-sporting populations (Scharfen & Memmert, 2019). Within this meta-analysis, a study from Verburgh, Scherder, et al. (2014) compared the EFs from highly talented junior football players to aged-matched amateur football players. The authors reported that EFs could differentiate between the two groups with high accuracy (89%), inferring that high-level populations yield better general cognitive abilities than lower level athletes within the same domain, and that EFs could therefore be used as a prognostic tool for talent identification. The concept of EFs being a new prognostic tool to discover new talent has been recently put to the test, showing measurable differences in EFs between selected and deselected academy players (Sakamoto et al., 2018). However, a limitation of this meta-analysis from Scharfen & Memmert (2019) is that the analysis of the EFs literature encompassed a variety of methodologies in various athletic populations, ages, differences in level of expertise, and cognitive assessments amongst other variables; all which may have exaggerated the overall suggestion that EFs is important in athletes. Additionally, differences in sports outside of football have not shown distinguishable differences in EFs in other team sports such as ice hockey (Lundgren et al., 2016) and basketball (Kida et al., 2005).

The meta-analysis by Scharfen and Memmert (2019) also stated that it remains difficult to confirm whether it is the chronological age (i.e. nature) or the amount of sport-specific playing experience of the participant (i.e. nurture) that is the main contributor to better cognitive functions in high performing athletes. Previous research has provided indications that playing sport can improve EFs in junior football athletes (8-12 years old) (Verburgh, Scherder, Van Lange, & Oosterlaan, 2016). Similarly, game-based exercise was related to better inhibitory control, and coordination training was associated with better working memory in junior tennis players (6-12 year old) (Ishihara et al., 2017). Furthermore, simple response times were faster in baseball players with higher levels of experience (Nakamoto & Mori, 2008). Additional research found that elite strategic sport athletes (i.e. sports requiring athletes to adapt to the dynamic environment such as football and ball, ice hockey) are better able to adjust to the changing demands of the task compared to static sport athletes (i.e. self-paced sports with stable circumstances such as swimming and athletics), which may be attributed to the differences in the cognitive demands of the sport (Krenn et al., 2018).

Accordingly, playing sport engages EFs and may in turn alter the developmental curves of EFs. This relationship may further extend into position-specific differences within the same sport (Scharfen & Memmert, 2019), as the in-game demands placed on a goalkeeper are very different from those placed on midfielders (Saygin et al., 2016), potentially influencing EFs trajectories over time. However, little is known about the influence that being immersed in a high-performance sport has on EFs. Developmental studies of EFs in athletic populations are lacking, limiting the generalizability of existing longitudinal EFs studies from general to athletic populations. General population studies reveal that EFs become ‘online’ around the age of eight (Ardila & Rosselli, 1994), and age-related improvements occur rapidly from late childhood into adolescence (12-15 y) and continue to improve at a slower rate into young-adulthood (≥18 y) (Huizinga, Dolan, & van der Molen, 2006; Zelazo & Müller, 2002). Indeed, adult levels of performance on such tasks is attained between the ages of 12-15 (Diamond, 2002; Huizinga et al., 2006), yet maximal expression of EFs is apparent around 20 years old to which EFs begin to plateau (Li et al., 2004). Seemingly, sport induced changes may be observed in an earlier onset of the rapid development of EFs during adolescence, or perhaps prolonging cognitive decline during adulthood.

One argument against the potential influence of a sporting environment improving one's EFs is that a large body of literature exists outside the sporting domain that disagrees with this concept. Genetic research reports that EFs is a natural ability that is hereditary dominated, reporting that 99% of EFs can be attributable to heritable genetic influences, with only trivial (1%) contributions from environmental influences (Friedman et al., 2008); indicating that people are born with these abilities rather than developed according to their environment. Contrastingly, sporting expertise is a competency, which is a developmental construct that improves with practice. Thus, although natural abilities are a part of the foundation that a competency is built upon, there has been little evidence to support that a transfer exists between these two constructs (Gagné, 2004). In other words, it has not yet been clearly demonstrated that an improvement in one's EFs has any parallel improvements in football performance, or vice versa. Therefore, it is likely that the role of EFs in sport is similar to how other natural abilities are relevant for performing in other competencies; being that a certain level of a natural ability is required to enter a certain field, but any further expression is not related to improved accomplishment within the competency. This is known as the "threshold" hypothesis. For instance, IQ is also a natural ability that contributes to creativity. Jauk et al. (2013) found that lower thresholds are required to produce one original idea (~86 IQ points), and a higher IQ was required (~120 IQ points) in order to produce a higher quantity of ideas. Yet any further expression of IQ after 120 points did not further improve creativity.

Together, there remains a debate on the importance of EFs in sport and the validity of using EFs for talent identification in athletes. On one hand, researchers have advocated the importance of EFs in sport, and therefore warrant the use of EF testing as a prognostic tool for talent identification. However, researchers also argue that measuring EFs cannot predict future sporting success, as there is no supporting literature to demonstrate a far transfer [i.e. transfer between contexts that are very unrelated and independent of each other (Barnett & Ceci, 2002)] between a natural ability and a competency. Therefore, there are significant gaps in the literature in sport that need to be addressed. First, no study has documented age-related changes in EFs that may occur throughout the entire phase of adolescence into adulthood in a high-level team sport population. Second, it remains unknown if there are factors associated to high-level football training that may influence age-related changes or are such trajectories merely a reflection of the normal maturation of the central nervous system. Therefore, this study aims to examine whether chronological age, years of experience playing football and playing position influence the developmental curves of EFs in a large homogenous population of high-level football players. Contrary to the current literature surrounding EFs in football athletes, and in accordance with other natural abilities' limited influence on performance within a competency, it is hypothesized that EFs are not related to football experience, and that the EF trajectories observed are reflecting the natural development of the central nervous system.

3.3 Materials and methods

Participants. Data were collected semi-annually from the 2016/17 to the 2018/19 season. Collectively, 343 individual youth male football players from nine age groups (U12 to Seniors; age range: 10.34 – 34.72 years old; experience range: 5 – 22 years) representing a high-level German Bundesliga club participated in this study. Collectively, a total of 1018 observations was entered into the analysis, where one data point represents a single player's participation in the testing battery. Across the dataset, absent data due to participants′ missing testing sessions or specific data points that contributed to multivariate non-normality resulted in varied working samples for each analysis. Furthermore, an outlier labelling rule for the precued choice response time task was used following the methods outlined by Hoaglin, Iglewicz, and Tukey (1986). This labelling rule identified outliers when they were outside of interval derived from multiplying each participant's interquartile range (IQR) by 1.5 and adding it to or subtracting it from the 25th and 75th percentiles respectively (i.e. data points that were not within -2.68 to +2.68 z-scores) and therefore discarded. More specific details of the working sample for each analysis can be found in Supplementary Table 1. Prior to commencement of this study, informed consent and assent for all players was received, and the Institutional Ethics Committee approved this study.

Procedures and apparatus. Players conducted four individual cognitive assessments aimed at measuring higher level cognitive functioning. Each age group was assessed on a separate day within a six-week period during pre-season. The order in which the assessments were conducted was randomised. The assessments were conducted in the same room, apart from the Helix that was stationed in another room inside the same building at the football club. Staff members remained in the testing rooms to give standardized instructions and monitor each player's performance. All assessment had a standardized familiarisation protocol prior to commencing the experimental trials. Each cohort was separated into three groups consisting of five to six players depending on the squad size. Testing required approximately 40 minutes per group to explain, have sufficient practice trials and to complete all the test, with two minutes rest between each assessment. The methodology used below is a replication of a previous methodology adopted by Beavan et al. (2019).

3.3.1 Vienna Test System: Determination Test

The Determination Test (Schufried GmbH, Austria) is a complex multi-stimuli reaction test involving the combination of five different coloured stimuli and two acoustic signals (2000 Hz high and 100 Hz low tone) for finger pressing, and two pedal stimuli for the feet. These stimuli corresponded to the pressing of appropriate buttons on the response panel and foot pedals. The determination test aims to measure reactive stress tolerance and the associated reaction speed. The participant must remain composed whilst the quick succession of the single pairing of stimulus and response lasting four minutes. 'Correct responses' describes the total number of accurate responses within the four minutes (DT: Correct), and 'response time' is the median response time (s) from the appearance of a stimulus to pressing of the correct button (DT: RT). The validity and reliability of the Vienna Test System has been confirmed by a variety of studies (Ljac, Witkowski, Gutni, Samovarov, & Nash, 2012; Schuhfried, 2001; Whiteside, Parker, & Snodgrass, 2003) and been previously been used in high-level football players (Baláková, Boschek, & Skalíková, 2015; Beavan et al., 2019).

3.3.2 Vienna Test System: Response Inhibition Test

The response inhibition test (Schufried GmbH, Austria) uses a stop signal paradigm. In each trial, the player is presented with an arrow either pointing left or right, to which he must respond by pressing the corresponding button. Each arrow is displayed for one second, and the time before the subsequent arrow appears is also one second. Seventy-six stimuli are ‘go trials’, with the other 24 stimuli having a tone at a pitch of 1000 Hz for 100 ms (stop signal). The player must then suppress the already initiated response, known as ‘stop trials’. The time between the presentation of the stimulus and the tone is dependent on the player’s performance (recorded as the mean reaction time in seconds (VTS: RT)) being that if the player responds correctly to a stop signal trial, the interval for the next stop stimuli will occur 50 ms later, and vice versa. Therefore, the correct response to the stimuli will continually progress in difficulty (minimum 50 ms; maximum 350 ms). The dependent variable that reflects the latency of the inhibitory process is stop signal reaction time (VTS: SSRT). The VTS: SSRT is calculated by deducting the mean stop signal delay from the mean reaction time (s).

3.3.3 Helix

The Helix (SAP, Walldorf, Germany) is a multiple object tracking assessment. The player stands facing a 180o curved screen (7 m width x 2.16 m height) and must track four out of eight simulated football players presented. The simulated players run around a football field for eight seconds in a randomized fashion and return to back to the start line up. Players must then identify the four players they were required to track. Players had four practice trials, and ten marked trials. The maximum score is 40 points, and is presented as a percentage, where 100% represents 40/40. There was no time pressure to provide a response. The concept of multiple object tracking has been thoroughly investigated, with Faubert and Sidebottom (2012) highlighting the use of object tracking in sport.

3.3.4 Precued Choice Response Time Task

Participants were required to press the button on a joystick panel associated with a stimulus circle presented on the laptop screen as fast and accurate as possible. The PCRTT was developed using Unity software (Unity, Version 5.4.0f3, 2016). Four blank stimulus circles were presented in a horizontal line, with one circle turning yellow in colour after a randomised (2-4 second) fore-period length. Each circle had a diameter of 512 pixels and an edge width of 5 pixels on a 13.2-inch display. Prior to the appearance of the stimulus, a three second countdown timer was shown. After the appearance of the four stimulus circles, a small dot appeared for 43 ms in the centre of one stimulus circle, 86 ms prior to the circle turning yellow. 24 trials were conducted. 12 trials had the small dot appear in the same circle as the yellow dot (congruent) and the other 12 trials had the dot appear in a different circle to the yellow dot (incongruent). Response time (ms) was measured as the duration between the appearance of the stimulus circle (turned yellow) on the computer screen and the moment the button was pressed by the participant. Three variables are derived from this test: i) response time to only the congruent trials (PCRTT: C), ii) response time to only the incongruent trials (PCRTT: IC), and iii) response inhibition being the sum of the response times to congruent minus the sum of the response times to incongruent trials (PCRTT: RespInhib). This test has been previously used in both general (Barela, Rocha, Novak, Fransen, & Figueiredo, 2019) and high-level athletic populations between youth and adults (Beavan et al., 2019), highlighting its use as measure of EFs.

Statistical analysis. To investigate the contribution of age, experience and playing position on a variety of EFs assessments, a series of linear mixed models were developed. A stepwise approach was used in which additional predictor was added to the model with each step, and model fit was evaluated using the Akaike's Information Criterion (AIC), observation of increases in degrees of freedom, a -2 log-likelihood ratio test and the normal distribution of the models' residuals. The response variables entered into the models were: DT: Correct, DT: RT, VTS: RT, VTS: SSRT, Helix: Correct, PCRTT: C, PCRTT: IC, and PCRTT: RespInhib. Age, experience, and playing position (fixed factors) in addition to players (random factor) were entered as predictors into the model to account for the random variance associated with the clustering of players' repeated measures. Separate linear mixed models were run for age and experience with the random factors due to the high collinearity between them.

Prior to the analysis, the linearity of relationships assumption was assessed. Additionally, following analysis, the model fit for each model was analysed through the normal distribution of model residuals using a quantile-quantile plot and through a Shapiro-Wilk test of normality. When observing the scatterplots of each response variable from each test against both age and experience, they appeared to be non-linear. Therefore, each response variable was log transformed in an attempt to improve the model fit, reduce skewness and make patterns more interpretable. However, the logged values did not improve the model fit according to the aforementioned criteria with respect to the non-logged values. As the scatterplots demonstrated positive non-linear relationships with a negatively accelerated curve in older athletes, this warranted the investigation of a second order polynomial model for both age and experience. The significance level for the -2 log-likelihood ratio tests was set at $p<0.05$, and an estimate precision was provided using Wald-based 95 % confidence intervals. Further detailed outline of the statistical procedure used in this study is presented in Supplementary Table 2.

3.4 Results

Both linear and non-linear mixed effects models were used, where the individual players' intercepts are allowed to vary randomly (player ID). Sixteen separate models analysed the contribution of age (n=8) and experience (n=8) on a variety of EF assessments. Second order polynomial models for both age (age^2) and experience (experience^2) appeared to best fit the data compared to the linear models' values using both non-logged and logged response variables. Collectively, these second order polynomial models indicated that a positive non-linear relationship exists between age, experience and performance on EF tests, accounting for the random variance associated with repeated observations clustered within players. This relationship is also negatively accelerated, meaning that EF performance increases rapidly during adolescents (12-17 years) and into the initial stages of early adulthood (≥18-21), but improvements begin to diminish after this phase.

Age. Two models (DT: Correct & DT: RT) were retained where there was a significant interaction effect with age^2 and playing position ($p<0.001$). The remaining six models that were retained had only a significant age^2 contribution to explaining the variance in the response variable.

Table 1. Retained models that explain the effect of age and playing position on players' executive functions. [a] indicates the best fitting model based on the AIC value and -2log-likelihood ratio test. PCRTT = precued choice reaction time task, RT = response time, DT = determination test, SSRT = stop signal reaction time, RespInhib = response inhibition.

	AIC	p-value	Chi2	R2 fixed only (%)	R2 random + fixed (%)	df
Determination Test: Number of Correct Answers						
[a] Final model: lmer (DT: Correct ~ Age + I(Age^2) + Playing Position + Age*Playing Position + (1|Player))						
Null Model: DT: Correct ~ 1 + (1|Player)	9833.6			0	68	1, 3
Random intercepts model: Age	9604.5	<0.001	231.15	32	82	1, 4
Random intercepts model: Age2	9438.5	<0.001	167.94	44	85	1, 5
Random intercepts model: Age^2 + Playing Position	9438.4	0.106	6.13	44	85	3, 8
[a] Random intercepts model: Age^2 * Playing Position	9478.4	<0.001	25.98	45	86	6, 11
Determination Test: Response Time						
[a] Final model: lmer (DT: RT ~ Age + I(Age^2) + Playing Position + Age*Playing Position + (1|Player))						
Null Model: DT: RT ~ 1 + (1|Player)	-3219.7			0	58	1, 3
Random intercepts model: Age	-2564.1	<0.001	246.37	30	74	1, 4
Random intercepts model: Age^2	-2861.0	<0.001	298.90	54	87	1, 5
Random intercepts model: Age^2 + Playing Position	-2863.1	0.043	8.14	55	87	1, 8
[a] Random intercepts model: Age^2 * Playing Position	-2891.3	<0.001	34.16	57	87	1, 11
Stop Signal Reaction Time						
[a] Final model: lmer (VTS: SSRT~ Age + I(Age^2) + (1|ID))						

Null Model: VTS: SSRT ~ 1 + (1|Player)	-2711.6			0	33	1, 3
Random intercepts model: Age	-2732.5	<0.001	23.00	4	36	1, 4
[a] Random intercepts model: Age^2	-2774.7	<0.001	44.16	10	40	1, 5
Random intercepts model: Age^2 + Playing Position	-2774.6	0.117	5.89	11	40	3, 8
Random intercepts model: Age^2 * Playing Position	-2774.0	0.080	11.25	11	40	6, 11
Vienna Test System's Response Inhibition Test: Reaction Time						
[a] Final Model: lmer (VTS: RT ~ Age + I(Age^2) + (1|ID))						
Null Model: RespInhib ~ 1 + (1|Player)	-2279.0			0	42	1, 3
Random intercepts model: Age	-2283.3	0.012	6.39	1	43	1, 4
[a] Random intercepts model: Age^2	-2328.8	<0.001	53.80	8	47	2, 5
Random intercepts model: Age^2 + Playing Position	-2328.7	0.115	5.93	9	48	3, 8
Random intercepts model: Age^2 * Playing Position	-2323.5	0.345	6.74	9	48	6, 11
Precued Choice Reaction Time Task: Response Inhibition						
[a] Final model: lmer (PCRTT: RespInhib ~ Age + I(Age^2) + (1|ID))						
Null Model: PCRTT: RespInhib ~ 1 + (1|Player)	-2316.2			0	<1	1, 3
Random intercepts model: Age	-2314.2	0.915	0.01	<1	<1	1, 4
[a] Random intercepts model: Age^2	-2320.1	0.019	7.95	1.6	1.6	2, 5
Random intercepts model: Age^2 + Playing Position	-2314.3	0.975	0.21	1.6	1.6	4, 7
Random intercepts model: Age^2 * Playing Position	-2211.5	0.757	3.40	2.1	2.1	7, 10

Choice Reaction Time Task: Congruent Response Times						
[a] Final Model: lmer (PCRTT: C ~ Age + I(Age^2) + (1|ID))						
Null Model: PCRTT: C ~ 1 + (1|ID))	-1495.4			0	40	1, 3
Random intercepts model: Age	-1507.1	<0.001	13.63	3	41	1, 4
[a] Random intercepts model: Age^2	-1515.6	0.001	10.54	6	44	1, 5
Random intercepts model: Age^2 + Playing Position	-1510.5	0.833	0.87	6	44	3, 8
Random intercepts model: Age^2 * Playing Position	-1510.0	0.379	6.41	8	45	6, 11
Choice Response Time Task: Incongruent Response Times						
[a] Final Model: lmer (PCRTT: IC ~ Age + I(Age^2) + (1|ID))						
Null Model: PCRTT: IC ~ 1 + (1|ID))	-1514.2			0	37	1, 3
Random intercepts model: Age	-1525.0	<0.001	12.74	3	39	1, 4
[a] Random intercepts model: Age^2	-1540.2	<0.001	17.20	8	42	1, 5
Random intercepts model: Age^2 + Playing Position	-1535.0	0.852	0.79	8	43	3, 8
Random intercepts model: Age^2 * Playing Position	-1533.4	0.514	5.24	9	43	6, 11
Helix						
[a] Final Model: lmer (Helix: Correct~ Age + I(Age^2) + (1|ID))						
Null Model: Helix: Correct ~ 1 + (1|ID))	3768.9			0	29	1, 3
Random intercepts model: Age	3746.9	<0.001	23.98	6	32	1, 4
[a] Random intercepts model: Age^2	3761.6	0.003	8.74	7	33	1, 5

Random intercepts model: Age^2 + Playing Position	3742.4	0.290	3.75	8	34	3, 8
Random intercepts model: Age^2 * Playing Position	3793.6	5.620	0.47	9	34	6, 11

For each advancing year, performance increased significantly in DT: Correct (9 points, 95 % CI: 7.16 – 10.77 points; $p<0.001$), DT: RT (-0.017 s; 95 % CI: -0.02 - -0.013 s, $p<0.001$), VTS: SSRT (-0.005 s; 95 % CI: -0.007 - -0.002 s, $p<0.001$), VTS: RT (-0.003 s, 95 % CI:-0.007 – 0.0 s, $p=0.042$), and the Helix: Correct (0.88 %, 95 % CI: 0.3 - 1.5 %; $p=0.005$). However, there were no significant improvements in the PCRTT task in either the congruent trials (-0.001 s, 95 % CI:-0.004 – 0.002 s, $p=0.54$), incongruent trials (-0.001 s, 95 % CI:-0.004 – 0.002 s, $p=0.716$), or response inhibition (<0.001 s, 95 % CI: -0.001 – 0.002 s, $p<0.53$).

Across each response variable, age only explained a low to moderate percentage (0 – 57 %; marginal explained variance: explained variance associated with the fixed effects only = mEV)) in only two parameters (DT: Correct and RT), and a low percentage (0 – 11 %) of the variance in the remaining six EF parameters. Although including random effects (conditional explained variance: fixed + random effects = cEV) improved the accuracy of the models for every parameter (21.2 ± 19.4 % improvement), a majority of the variance in the response variable was left unexplained for the remaining models (see Table 2).

Experience. Only one model retained (PCRTT: RespInhib) reported an interaction effect with experience and playing position ($p=0.006$). Additionally, two models (DT: RT and VTS: RT) were improved when experience^2 was used. However, the remaining five (DT: Correct, VTS: SSRT, PCRTT: C, PCRTT: IC, and Helix: Correct) that were retained demonstrated a significant ($p\leq0.05$) contribution of experience to performance on the EF tests. See Table 3 for the model parameters with experience.

Table 2. Least square means, 95% confidence intervals (CI), standard error (SE), degrees of freedom (DF), t-values and random effect parameters from the retained linear mixed models investigating the effects of age and playing position on players' EF variables.

	Estimate	95% CI	SE	df	t-value	p-value
Determination Test: Correct Number of Answers						
Intercept: Defender	-169.963	-220.14 - -119.78	25.603	639	-6.64	<0.001
Age	41.872	36.83 - 46.92	2.575	662	16.26	<0.001
I(Age^2)	-0.903	-1.03 - -0.77	0.067	634	-13.52	<0.001
Playing Position: Forward	51.840	12.24 - 91.45	20.207	456	2.57	0.01
Playing Position: Goalkeeper	-31.476	-82.47 - 1952	26.020	422	-1.21	0.23
Playing Position: Midfield	0.623	-35.32 - 36.57	18.339	514	0.03	0.97
Age*Playing Position: Forward	-3.277	-5.55 - -1.00	1.161	457	-2.82	<0.001
Age*Playing Position: Goalkeeper	2.444	-0.54 - 5.43	1.523	441	1.61	0.11
Age*Playing Position: Midfield	0.435	-1.69 - 2.56	1.084	510	0.40	0.69
Determination Test: Response Time						
Intercept: Defender	1.748	1.654 - 1.841	0.048	505	36.61	<0.001
Age	-0.107	-0.117 - -0.098	0.005	527	-22.25	<0.001
I(Age^2)	0.002	0.002 - 0.003	<0.001	506	19.53	<0.001
Playing Position: Forward	-0.062	-0.135 - 0.010	0.037	357	-1.68	0.09
Playing Position: Goalkeeper	0.173	0.079 - 0.266	0.048	321	3.63	<0.001
Playing Position: Midfield	-0.011	-0.077 - 0.055	0.034	403	-0.32	0.75
Age*Playing Position: Forward	0.004	0.000 - 0.008	0.002	359	1.89	0.06

Age*Playing Position: Goalkeeper	-0.012	-0.017 - -0.006	0.003	334	-4.25	<0.001
Age*Playing Position: Midfield	0.000	-0.004 - 0.004	0.002	401	-0.13	0.90
Stop Signal Reaction Time						
Intercept: Defender	0.470	0.392 - 0.547	0.040	431	11.87	<0.001
Age	-0.031	-0.039 - -0.023	0.004	444	-7.69	<0.001
I(Age^2)	0.001	0.001 - 0.001	0.000	446	6.81	<0.001
Playing Position: Forward	-0.021	-0.078 - 0.036	0.029	383	-0.72	0.47
Playing Position: Goalkeeper	0.033	-0.039 - 0.104	0.036	355	0.90	0.37
Playing Position: Midfield	-0.047	-0.100 - 0.007	0.027	404	-1.72	0.09
Age*Playing Position: Forward	0.002	-0.002 - 0.005	0.002	405	0.95	0.34
Age*Playing Position: Goalkeeper	-0.002	-0.006 - 0.002	0.002	364	-0.92	0.36
Age*Playing Position: Midfield	0.002	-0.001 - 0.005	0.002	419	1.40	0.16
Vienna Test System’s Response Inhibition Test: Reaction Time						
Intercept: Defender	0.801	0.697 - 0.901	0.052	474	15.43	<0.001
Age	-0.037	-0.047 - -0.026	0.005	495	-6.99	<0.001
I(Age^2)	0.001	0.001 - 0.001	<0.001	506	6.67	<0.001
Playing Position: Forward	0.009	-0.067 - 0.084	0.039	430	0.22	0.82
Playing Position: Goalkeeper	0.023	-0.07 - 0.117	0.048	386	0.49	0.63
Playing Position: Midfield	-0.011	-0.081 - 0.058	0.036	448	-0.32	0.75
Age*Playing Position: Forward	0.001	-0.004 - 0.005	0.002	464	0.35	0.72

Age*Playing Position: Goalkeeper	-0.001	-0.007 - 0.004	0.003	412	-0.41	0.69
Age*Playing Position: Midfield	0.001	-0.003 - 0.005	0.002	471	0.50	0.62
Precued Choice Response Time Task: Response Inhibition						
Intercept: Defender	-0.083	-0.121 - -0.045	0.020	496	-4.24	<0.001
Age	0.006	0.002 - 0.010	0.002	496	3.16	<0.001
I(Age^2)	0.000	<0.001 - <0.001	<0.001	496	-3.11	<0.001
Playing Position: Forward	0.003	-0.024 - 0.03	0.014	496	0.24	0.81
Playing Position: Goalkeeper	-0.006	-0.041 - 0.028	0.018	496	-0.37	0.71
Playing Position: Midfield	0.020	-0.007 - 0.047	0.014	496	1.48	0.14
Age*Playing Position: Forward	0.000	-0.002 - 0.001	0.001	496	-0.21	0.83
Age*Playing Position: Goalkeeper	0.000	-0.002 - 0.002	0.001	496	0.37	0.71
Age*Playing Position: Midfield	-0.001	-0.003 - <0.001	0.001	496	-1.44	0.15
Precued Choice Response Time Task: Congruent Response Times						
Intercept: Defender	0.690	0.586 - 0.793	0.053	296	13.07	<0.001
Age	-0.017	-0.027 - -0.006	0.005	302	-3.17	0.002
I(Age^2)	0.000	<0.001 - 0.001	<0.001	315	3.20	0.002
Playing Position: Forward	0.030	-0.042 - 0.102	0.037	302	0.81	0.417
Playing Position: Goalkeeper	0.079	-0.009 - 0.167	0.045	328	1.77	0.078
Playing Position: Midfield	0.061	-0.011 - 0.132	0.036	312	1.67	0.096

Age*Playing Position: Forward	-0.002	-0.006 - 0.002	0.002	321	-0.79	0.428
Age*Playing Position: Goalkeeper	-0.005	-0.010 - <0.001	0.003	352	-2.01	0.045
Age*Playing Position: Midfield	-0.004	-0.008 - 0.001	0.002	318	-1.71	0.088
Precued Choice Response Time Task: Incongruent Response Times						
Intercept: Defender	0.760	0.661 - 0.859	0.051	294	15.00	<0.001
Age	-0.022	-0.032 - -0.012	0.005	300	-4.22	<0.001
I(Age^2)	0.001	<0.001 - 0.001	<0.001	315	4.22	<0.001
Playing Position: Forward	0.026	-0.043 - 0.095	0.035	301	0.74	0.463
Playing Position: Goalkeeper	0.079	-0.006 - 0.163	0.043	329	1.82	0.069
Playing Position: Midfield	0.035	-0.034 - 0.103	0.035	313	0.98	0.326
Age*Playing Position: Forward	-0.001	-0.005 - 0.003	0.002	321	-0.70	0.486
Age*Playing Position: Goalkeeper	-0.005	-0.010 - <0.001	0.003	355	-2.04	0.043
Age*Playing Position: Midfield	-0.002	-0.006 - 0.002	0.002	319	-1.06	0.291
Helix						
Intercept: Defender	35.161	10.43 - 59.89	12.616	300	2.79	0.006
Age	4.945	1.95 - 7.94	1.529	299	3.24	0.001
I(Age^2)	-0.128	-0.22 - -0.04	0.047	296	-2.72	0.007
Playing Position: Forward	-0.983	-14.8 - 12.84	7.051	276	-0.14	0.889
Playing Position: Goalkeeper	-11.148	-30.51 - 8.22	9.880	259	-1.13	0.260
Playing Position: Midfield	3.405	-9.18 - 15.99	6.419	271	0.53	0.596

Age*Playing Position: Forward	-0.030	-0.90 - 0.84	0.445	270	-0.07	0.947
Age*Playing Position: Goalkeeper	0.647	-0.60 - 1.89	0.634	256	1.02	0.308
Age*Playing Position: Midfield	-0.179	-0.98 - 0.62	0.407	269	-0.44	0.661

Table 3. Retained models that explain the effect of years of playing experience (Exp) and playing position on players' executive functions. [a] indicates the best fitting model based on the AIC value and -2log-likelihood ratio test. PCRTT = choice reaction time task, RT = response time, DT = determination test, SSRT = stop signal reaction time, RespInhib = response inhibition.

	AIC	p-value	Chi^2	R2 fixed only (%)	R2 random + fixed (%)	df
Determination Test: Number of Correct Answers						
[a] Final Model: lmer (DT: Correct~ Exp + I(Exp^1) + (1|Player))						
Null Model: DT: Correct ~ 1 + (1|Player)	5551.1			0	67	1, 3
[a] Random intercepts model: Exp	5339.4	<0.001	213.64	47	90	1, 4
Random intercepts model: Exp^2	5341.4	0.840	0.04	47	90	1, 5
Random intercepts model: Exp^2 + Playing Position	5345.1	0.666	2.38	47	90	4, 8
Random intercepts model: Exp^2 * Playing Position	5349.6	0.797	3.85	46	90	7, 11
Determination Test: Response Time						
[a] Final Model: lmer (DT: RT~ Exp + I(Exp^2) + (1|Player))						
Null Model: DT: RT ~ 1 + (1|Player)	-1309.6			0	57	1, 3
Random intercepts model: Exp	-1509.1	<0.001	201.53	48	87	1, 4
[a] Random intercepts model: Exp^2	-1521.6	<0.001	14.50	49	90	1, 5
Random intercepts model: Exp^2 + Playing Position	-1517.8	0.536	2.18	49	91	3, 8
Random intercepts model: Exp^2 * Playing Position	-1514.2	0.600	4.57	49	91	6, 11
Stop Signal Reaction Time						

[a] Final Model: lmer (VTS: SSRT~ Exp + I(Exp^1) + (1|Player))						
Null Model: VTS: SSRT ~ 1 + (1|Player)	-1493.8			0	32	1, 3
[a] Random intercepts model: Exp	-1514.9	<0.001	23.11	7	37	1, 4
Random intercepts model: Exp^2	-1515.8	0.084	2.98	7	37	1, 5
Random intercepts model: Exp^2 + Playing Position	-1511.9	0.281	5.07	8	37	4, 8
Random intercepts model: Exp^2 * Playing Position	-1511.5	0.157	10.61	8	38	7, 11
Vienna Test System's Response Inhibition Test: Reaction Time						
[a] Final Model: lmer (VTS: RT ~ Exp + I(Exp^2) + (1|Player))						
Null Model: VTS: RT ~ 1 + (1|Player)	-1375.9			0	42	1, 3
Random intercepts model: Exp	-1384.5	0.001	10.60	4	45	1, 4
[a] Random intercepts model: Exp^2	-1387.7	0.022	5.17	5	46	1, 5
Random intercepts model: Exp^2 + Playing Position	-1383.0	0.732	1.29	5	47	3, 8
Random intercepts model: Exp^2 * Playing Position	-1378.5	0.833	2.80	6	48	6, 11
Precued Choice Reaction Time Task: Response Inhibition						
[a] Final Model: lmer (PCRTT: RespInhib ~ Experience + I(Experience^2) + Playing Position + Experience*Playing Position + (1|ID))						
Null Model: PCRTT: RespInhib ~ 1 + (1|Player)	-784.2			0	11	1, 3
Random intercepts model: Exp	-782.6	0.518	0.42	<1	13	1, 4
Random intercepts model: Exp^2	-781.4	0.549	2.00	<1	15	2, 5
Random intercepts model: Exp^2 + Playing Position	782.4	0.145	8.21	3	20	5, 8
[a] Random intercepts model: Exp^2 * Playing Position	-789.5	0.006	21.30	7	20	8, 11

Precued Choice Response Time Task: Congruent Response Times						
[a] Final Model: lmer (PCRTT: C~ Exp + I(Exp^1) + (1|Player))						
Null Model: PCRTT: C ~ 1 + (1|Player)	-998.14			0	46	1, 3
[a] Random intercepts model: Exp	-1004.0	0.005	7.86	3	46	1, 4
Random intercepts model: Exp^2	-1003.4	0.235	1.41	4	48	1, 5
Random intercepts model: Exp^2 + Playing Position	-999.1	0.540	2.11	5	48	4, 8
Random intercepts model: Exp^2 * Playing Position	-995.39	0.613	5.39	6	49	7, 11
Choice Response Time Task: Incongruent Response Times						
[a] Final Model: lmer (PCRTT: IC ~ Experience + I(Experience^1) + (1|ID))						
Null Model: PCRTT: IC ~ 1 + (1|ID)	-1006.4			0	43	1, 3
[a] Random intercepts model: Exp	-1016.9	<0.001	12.47	5	44	1, 4
Random intercepts model: Exp^2	-1018.3	0.066	3.38	7	46	1, 5
Random intercepts model: Exp^2 + Playing Position	-1013.5	0.328	4.62	7	47	4, 8
Random intercepts model: Exp^2 * Playing Position	-1009.3	0.497	6.37	8	47	7, 11
Helix						
[a] Final Model: lmer (Helix: Correct ~ Experience + I(Experience^1) + (1|ID))						
Null Model: Helix: Correct ~ 1 + (1|ID)	2271.8			0	31	1, 3
[a] Random intercepts model: Exp	2270.0	0.051	3.80	2	32	1, 4

Random intercepts model: Exp^2	2271.8	0.611	0.26	2	33	1, 5
Random intercepts model: Exp^2 + Playing Position	2274.2	0.440	3.76	3	34	4, 8
Random intercepts model: Exp^2 * Playing Position	2277.3	0.378	6.4172	4	34	7, 11

For a single year of experience playing football, players improved in the majority of each test: DT: Correct (17 points, 95 % CI:13.22 – 20.22 points, p<0.001), DT: RT (-0.036 s, 95 % CI: - 0.043 – 0.029 s, p<0.001), VTS: SSRT (-0.011 s, 95 % CI: -0.016 - -0.007 s, p <0.001), PCRTT: IC (-0.008 s, 95 % CI: -0.013 - -0.002 s, p=0.005) and PCRTT: RespInhib (0.010 s, 95 % CI: 0.004 – 0.016 s, p=0.002). However, there was no significant improvements in the VTS: RT (-0.004 s, 95 % CI: -0.010 – 0.002 s, p=0.168), the PCRTT: C (-0.004 s, 95 % CI: -0.01 – 0.001 s, p=0.140), or the Helix: Correct (0.40 %, 95 % CI: -0.4 – 1.2 %, p=0.309).

The amount of variance explained in the models with experience demonstrated similar results with age. Low to moderate mEV (0 – 49 %) values were reported in the DT: Correct and DT: RT, whereas only low mEV (0 – 8 %) were reported in the same remaining six parameters. Comparable with age, the inclusion of random effects improved the accuracy of the models for every parameter (35.6 ± 12.5 % cEV improvement), however the majority of the models also remained only moderately explained (see Table 4).

Playing Position. Playing position was not a strong contributor in the variance associated across most EF assessments. Only the DT: Correct and DT: RT models revealed a significant age*position interaction effect. In the Determination test, forwards have lower number of correct responses (-3.28 points, 95 % CI: -5.55 – 1.00 points, p<0.005) and have slower response times (0.004 s, 95 % CI: <0.001 – 0.008 s, p=0.06), whereas goalkeepers are faster (-0.012 s, 95 % CI, - 0.017- -0.006 s, p<0.001) and increased their number of correct responses (2.44 points, 95 % CI: -0.54-5.43 points, p=0.11), with respect to the defenders. However, there were no observable differences between midfielders and defenders in any test (see Table 1 & Table 2).

Table 4. Least square means, 95% confidence intervals (CI), standard error (SE), degrees of freedom (DF), t-values and random effect parameters from the retained linear mixed models investigating the effects of experience and playing position on players' EF variables.

	Estimate	95% CI	SE	df	t-value	p-value
Determination Test: Correct Number of Answers						
Intercept: Defender	95.300	39.67 - 150.93	28.384	373	3.36	0.001
Experience	16.771	7.71 - 25.84	4.625	427	3.63	0.000
I(Experience^2)	-0.007	-0.41 - 0.4	0.206	457	-0.03	0.974
Playing Position: Forward	15.918	-44.9 - 76.73	31.028	275	0.51	0.608
Playing Position: Goalkeeper	-6.115	-78.90 - 66.67	37.138	374	-0.17	0.869
Playing Position: Midfield	11.609	-36.97 - 60.19	24.786	314	0.47	0.640
Experience*Playing Position: Forward	-2.192	-7.88 - 3.50	2.902	319	-0.76	0.451
Experience*Playing Position: Goalkeeper	2.358	-4.56 - 9.27	3.528	462	0.67	0.504
Experience*Playing Position: Midfield	-0.907	-5.34 - 3.52	2.260	375	-0.40	0.688
Determination Test: Response Time						
Intercept: Defender	1.220	1.107 - 1.333	0.058	323	21.18	<0.001
Experience	-0.071	-0.089 - -0.053	0.009	387	-7.56	<0.001
I(Experience^2)	0.002	0.001 - 0.002	<0.001	425	3.72	<0.001
Playing Position: Forward	-0.021	-0.146 - 0.103	0.064	227	-0.34	0.737
Playing Position: Goalkeeper	-0.030	-0.178 - 0.118	0.075	323	-0.40	0.691
Playing Position: Midfield	-0.076	-0.174 - 0.023	0.050	262	-1.50	0.135

Experience*Playing Position: Forward	0.003	-0.009 - 0.014	0.006	270	0.45	0.653
Experience*Playing Position: Goalkeeper	-0.001	-0.015 - 0.013	0.007	430	-0.09	0.928
Experience*Playing Position: Midfield	0.006	-0.003 - 0.015	0.005	328	1.41	0.159
Stop Signal Reaction Time						
Intercept: Defender	0.309	0.232 - 0.386	0.039	181	7.85	<0.001
Experience	-0.019	-0.032 - -0.006	0.007	186	-2.86	0.005
I(Experience^2)	0.000	<0.001 - 0.001	0.000	192	1.24	0.216
Playing Position: Forward	-0.061	-0.144 - 0.021	0.042	183	-1.45	0.149
Playing Position: Goalkeeper	-0.044	-0.146 - 0.058	0.052	180	-0.84	0.403
Playing Position: Midfield	-0.076	-0.142 - -0.010	0.034	188	-2.25	0.026
Experience*Playing Position: Forward	0.007	-0.001 - 0.015	0.004	174	1.75	0.082
Experience*Playing Position: Goalkeeper	0.003	-0.007 - 0.014	0.005	188	0.67	0.506
Experience*Playing Position: Midfield	0.007	0.001 - 0.013	0.003	185	2.17	0.032
Vienna Test System’s Response Inhibition Test: Reaction Time						
Intercept: Defender	0.558	4.66 - 0.65	0.047	208	11.82	<0.001
Experience	-0.018	-3.38 - 0.003	0.008	216	-2.32	0.021
I(Experience^2)	0.001	-3.31 - 0.001	<0.001	226	1.95	0.052
Playing Position: Forward	0.062	-3.31 -0.162	0.051	205	1.23	0.221

Playing Position: Goalkeeper	0.062	-6.167 - 0.019	0.063	216	0.98	0.328
Playing Position: Midfield	0.020	-5.922 - 0.099	0.040	210	0.50	0.621
Experience*Playing Position: Forward	-0.005	-1.393 - 0.005	0.005	200	-0.98	0.331
Experience*Playing Position: Goalkeeper	-0.005	-1.745 - 0.007	0.006	226	-0.87	0.385
Experience*Playing Position: Midfield	-0.001	-8.431 - 0.006	0.004	210	-0.29	0.776
Precued Choice Reaction Time Task: Response Inhibition						
Intercept: Defender	-0.167	-0.268 - -0.066	0.052	62	-3.24	0.002
Experience	0.015	-0.002 - 0.031	0.008	63	1.73	0.089
I(Experience^2)	0.000	-0.001 - 0.001	<0.001	64	-0.57	0.570
Playing Position: Forward	0.111	0.012 - 0.211	0.051	52	2.20	0.032
Playing Position: Goalkeeper	0.089	-0.057 - 0.234	0.074	47	1.19	0.240
Playing Position: Midfield	0.175	0.089 - 0.260	0.044	59	4.01	0.000
Experience*Playing Position: Forward	-0.009	-0.018-0.001	0.005	48	-1.93	0.060
Experience*Playing Position: Goalkeeper	-0.007	-0.021 - 0.007	0.007	44	-0.99	0.329
Experience*Playing Position: Midfield	-0.014	-0.021 - -0.006	0.004	55	-3.46	0.001
Precued Choice Response Time Task: Congruent Response Times						
Intercept: Defender	0.625	0.533 - 0.717	0.047	161	13.33	<0.001
Experience	-0.013	-0.028 - 0.001	0.008	160	-1.77	0.079
I(Experience^2)	0.000	<0.001 - 0.001	<0.001	163	1.31	0.193
Playing Position: Forward	-0.022	-0.113 - 0.068	0.046	155	-0.48	0.631

Playing Position: Goalkeeper	-0.070	-0.203 - 0.062	0.068	160	-1.04	0.300
Playing Position: Midfield	0.025	-0.052 - 0.102	0.039	163	0.64	0.523
Experience*Playing Position: Forward	0.002	-0.006 - 0.01	0.004	153	0.49	0.627
Experience*Playing Position: Goalkeeper	0.005	-0.007 - 0.018	0.006	159	0.86	0.392
Experience*Playing Position: Midfield	-0.002	-0.009 - 0.005	0.004	163	-0.55	0.584
Precued Choice Response Time Task: Incongruent Response Times						
Intercept: Defender	0.702	0.615 - 0.788	0.044	160	15.96	<0.001
Experience	-0.020	-0.034 - -0.005	0.007	158	-2.72	0.007
I(Experience^2)	0.001	<0.001 - 0.001	<0.001	160	1.78	0.077
Playing Position: Forward	-0.048	-0.134 - 0.037	0.044	152	-1.10	0.272
Playing Position: Goalkeeper	-0.084	-0.21 - 0.043	0.064	155	-1.30	0.196
Playing Position: Midfield	-0.026	-0.099 - 0.047	0.037	161	-0.70	0.485
Experience*Playing Position: Forward	0.004	-0.004 - 0.012	0.004	149	1.00	0.317
Experience*Playing Position: Goalkeeper	0.007	-0.005 - 0.019	0.006	153	1.08	0.284
Experience*Playing Position: Midfield	0.002	-0.005 - 0.009	0.003	160	0.63	0.530
Helix						
Intercept: Defender	75.124	62.6 - 87.7	6.40	152	11.73	<0.001
Experience	0.712	-1.5 - 2.9	1.12	160	0.64	0.53
I(Experience^2)	-0.016	-0.1 - 0.1	0.05	165	-0.30	0.77
Playing Position: Forward	-10.697	-24.3 - 2.9	6.96	157	-1.54	0.13

Playing Position: Goalkeeper	5.632	-11.1 - 22.3	8.53	120	0.66	0.51
Playing Position: Midfield	1.468	-10.0 - 12.9	5.85	153	0.25	0.80
Experience*Playing Position: Forward	0.779	-0.5 - 2.1	0.65	146	1.20	0.23
Experience*Playing Position: Goalkeeper	-0.472	-2.2 - 1.2	0.86	125	-0.55	0.59
Experience*Playing Position: Midfield	-0.109	-1.2 - 1.0	0.54	148	-0.20	0.84

When examining the models with experience, only the PCRTT: RespInhib had an observable interaction effect with playing position. With one year of additional experience, a noticeable improvement in response inhibition was observed in forwards (-0.009 s, 95 % CI: -0.018 - 0.001 s, p<0.060) and midfielders (-0.014 s, 95 % CI: -0.021 - -0.006 s, p<0.001) with respect to defenders, but goalkeepers did not demonstrate significant improvements with respect to any position (-0.007 s, 95 % CI: -0.021 – 0.007 s, p=0.329) (see Table 3 & Table 4).

Collectively, the three different fixed factors on the determination test score can be seen in Figure 3 as a demonstration of the developmental trajectories that are reflected throughout each test.

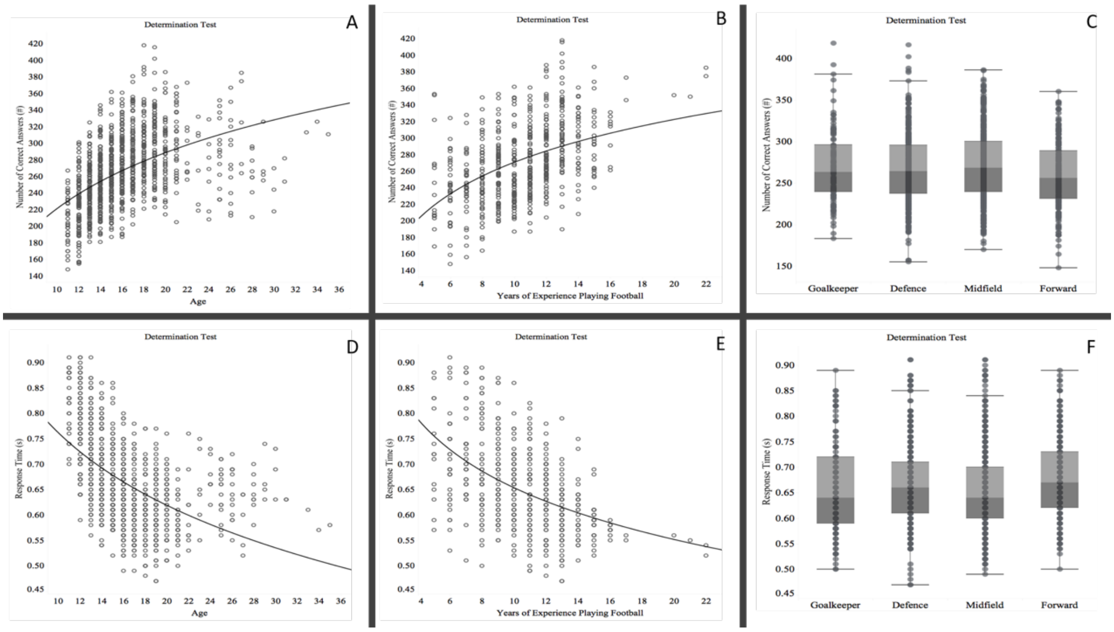


Figure 3. The individual contribution of age, experience and playing position on the determination test's number of correct answers (A-C) and response time (D-F).

3.5 Discussion

The primary aim of this study was to examine the contribution of chronological age, years of experience playing football and playing position upon measures of EFs in a large cohort of gifted and talented football players. Players' EFs were examined using four cognitive tests. The main finding of the study is that age and experience explain some of the variance consistently across each assessment but playing position did not appear to be a strong predictor of performance on EF tasks. Overall, the models indicate that age was a stronger predictor than experience across each assessment.

Research in cognitive psychology has previously reported that despite individual EFs following different developmental trajectories, collectively they are fully developed between the mid-adolescent and adult phase (Anderson, 2002), and reach an adult performance level at 15 years old (Huizinga et al., 2006). The current study demonstrates that the age-specific developmental curves of the high-level athletes appear to follow the theoretically predicted trends that are observed in general populations (Crone, Peters, & Steinbeis, 2017; Li et al., 2004; Zelazo et al., 2003), where individuals reached their maximum cognitive abilities at comparable ages (mid 20's). These findings are also aligned with the findings from a meta-analysis on EFs in athletes, where slightly better EFs in youth (<18 years of age) vs. adults (≥18 years of age) was observed (Scharfen & Memmert, 2019). Thus, the parallel EF trajectories between the general population and high-level sporting populations suggest that the increases of EFs of athletes within their adolescent phase may be largely attributed to the normal maturation of the central nervous system rather than sport-induced developments.

The large effect that age has on the EF trajectories is also demonstrated in the older adult athletes, where an apparent plateau in EF performance is observed. To explain, this plateau of EFs may be a result of cognitive decline, which normally is observed around the age of 24 in general populations (Crone et al., 2017). Since athletes demonstrate cognitive decline at the same age of the general population, this represents two main findings. First, it further supports that adult athletes must progressively rely on their domain-specific experience in order to continue to perform at a high level even with their natural abilities declining. This compensation effect is also apparent in other domains such as driving, where despite perception-reaction times becoming significantly worse between three groups with a mean age of 23, 30 and 62 years old, brake-movement time to stimuli did not change with age (Warshawsky-Livne & Shinar, 2002). Second, years of experience in a high-level sport do not seem to have a large effect on EF development, supported by the small to moderate explained variance from each EF test and years of playing football in this study. Recently, it has been proposed that there may be a dose-response relationship between engaging in sport-related activity and improved EFs (Scharfen & Memmert, 2019). This possible relationship has been supported by previous research reporting that aerobic exercise (Colcombe & Kramer, 2003; Kramer & Erickson, 2007) and resistance training (Chang & Etnier, 2009) can enhance cognitive and neural plasticity. Furthermore, more complex and cognitively demanding exercise such as participating in sport, also demonstrates improvements in EFs. A previous study in tennis reported a possible dose-response relationship with game-based training and coordination training with improved EFs in junior (< 12 years old) tennis athletes (Ishihara et al., 2017). However, although this may be possible in the younger age groups, the results from the current study do not seem to support that more engagement in high-performance sport improves EFs in athletes that are already competing at a high level of play.

If EFs are indeed positively affected by an increased exposure to sport, then a positive linear relationship should have been observed to represent a strong continuous relationship between increased EF performance with each year of playing sport in the current study. Furthermore, if that hypothesis holds true, older adult athletes should be able to suppress the onset of cognitive decline in comparison to the general population. Yet in the current study, the models with only experience as an independent variable demonstrated either no-relationship, or a negatively accelerated curve. This similarly indicates that the relationship between football experience and EFs may adhere to the 'threshold hypothesis'. It may be possible that the adolescent athletes tested in our sample may have already reached the necessary threshold level of EF performance required to play at a high level. Of note, athletes in this study's sample had already an average of seven years of experience when reaching the age of 12, and it is possible that any experience beyond this threshold does not continue to improve EFs. This threshold effect is not a new phenomenon, and has previously been demonstrated in other domains of cognitive functioning (Baird, 1985). For example, the relationship between intelligence and creativity is thought to be related until a certain threshold value, where any increase beyond the minimal level of intelligence has no more effect of improving creativity. The threshold of IQ varies across different indicators of creativity, but it is generally accepted that an IQ beyond 115-120 loses its impact on improving creativity, and where other factors become more relevant (Karwowski & Gralewski, 2013).

On another note, if the developmental trends reveal that EF performance begins to decrease when athletes are reaching the age where they become professional athletes, then the potential usefulness of assessing EFs for talent identification is questionable. Accordingly, the use of EF assessments may be better suited for the early detection of possible football players from a heterogenous cohort that does not yet play football at a high-level or who has limited experience, rather than in the identification of the best performers in a homogenous cohort of high-level players. There is also a large variation of performance on each EF assessment within each age group, and it is difficult to make any inferences of the importance of EFs in high-level sport when the variance of EF performance is so large. This large variation indicates that: i) the skills necessary to achieve excellence within a sport are multifaceted, and a deficiency in one domain such as lower EFs can be counteracted by a strength in another, known as the compensation phenomenon (e. g. better physical conditioning), ii) the role of EFs in sport remains unknown especially during periods of the rise (i.e. <15 years of age) and fall (>24 years of age). Albeit, this variation may also be attributed to many factors that this study did not consider; including the possible motivational differences within the professional group verses the younger cohorts, and different levels of playing ability within the same age group. More research should stratify players using alternative performance indicators (i.e. coaches' ratings of skill) and use more fixed factors in order to help explain the variance.

Longitudinal analyses are also warranted to study the relationship between EFs and football performance. Without longitudinal data, it is difficult to confirm whether a player with a lower EFs score can also be considered less talented (i.e. has a lower likelihood of reaching elite levels of football performance). Previous research has attempted to find differences in selected vs. deselected players, finding slightly higher EF averages in the selected players group (Sakamoto et al., 2018). However, their results also showed high variability within each group in addition to a large overlap between the groups, making the differences negligible and not practically relevant for being able to distinguish between better and worse players. Although, neither the current dataset nor previous research has been able to report whether the players that are achieving the lower scores are also being deselected in the coming years due to their inability to deal with the increasing demands of elite football on a cognitive level. Additionally, it remains uncertain whether the players that score the highest on EF assessments will in turn progress to the professional level. Therefore, future studies should investigate different break-points in the developmental trajectories of EFs, preferably in a way that can map out individual curves of youth athletes compared to a reference database in order to help understand what the normal expected variation is within a high-level athletic cohort, and to understand if there are specific developmental trends to the players that reach the highest level of adult level football. This type of analysis will also provide further insight into how athletes with the same amount of playing experience and age differ in their EF developmental patterns and follow up studies could track where the player has ended up in their future to expand on the study by Sakamoto et al. (2018).

We acknowledge a number of limiting factors that should be considered when interpreting the current data. First, despite the availability in the existing literature, a sample from the general population was not assessed alongside the sample of high-level football players. A progression from this study would be to assess the large range of non-athletic control groups on the same cognitive battery as presented in this study to directly compare their developmental trajectories. Second, various contextual variables may have influenced the attainment of scores across the battery of EFs. Variables such as motivation, players' contract situations, wellness, and emotional states all may influence the test results (Stiroh, 2007); but these variables have remained difficult to account for objectively in scientific research although may help to explain the large observed variance. It is also important to note that the data presented is a mixed longitudinal sample, meaning that the data are only approximations of true longitudinal growth and decline associated with age and experience. Long-term follow ups are required in the future that measure individual athletes with repeated measures. Despite these limitations, the current study still provides sufficient evidence that contradicts previous research that emphasised a stronger relationship between EFs and football performance. By demonstrating that age rather than football experience represents the biggest contributor to the development of EFs, serious doubts exist that EFs can be used as an indicator for future football talent within a homogenous population of high-level players when considering the threshold hypothesis. Future research should focus on whether assessing EFs has more value to help in the detection of potential talent from a heterogenous cohort that does not yet compete at a high-level (i.e. a large group of school kids), or in the identification of the best performers within a homogenous cohort of already competing athletes (i.e. high-level academy players likely to become adult-professionals).

3.6 Conclusion

The current study demonstrated that the age-related changes in cognitive abilities in high-level athletes develop parallel to general populations reported in previous research. The observed increases in EFs throughout adolescence into adulthood cannot be seen as independent from the normal effects of growth and maturation of the central nervous system, whereas years of experience playing their respective sport did not appear to be a large contributor to explain EF performance. Furthermore, the developmental curves represent that participating in sporting activities being expected to engage EFs is not a strong enough stimulus to protect against the natural cognitive decline in the age ranges measured in this study. The findings from measuring EFs in sport aligns well with previous research that also used domain-generic abilities to explain future success in a chosen competency. It is likely that the threshold hypothesis also exists for EFs in sport, where athletes must have a certain level of EF ability in order to compete at a high-level, but any further improvement beyond this minimal requirement is likely to not further improve sporting performance. Yet more longitudinal approaches are required in order to continue to understand the role that EFs play in sport and provide further insights into how EFs develop amongst individuals alongside other performance characteristics of an athlete.

Supplementary Table 1. Data included in the analysis for the models using chronological age.

Value	Brief Description	Total *n* Included in the Age Models	Total *n* Included in the Experience Models
Total Data Points	Each data point represents 1 player	1018	556
Age	Range: 10.34 – 34.72 years old Mean: 16.30 ± 3.85 years old	1018	-
Experience	Range: 5 – 22 years old Mean: 10.53 ± 2.82 years old	-	566
Personalized ID	Each player has their own unique # ID	343	147
Season	Which season a player was tested	2016-17 (342) 2017-18 (338) 2018-19 (338)	2016-17 (143) 2017-18 (217) 2018-19 (206)
Time of Test	Pre-season (Collected in July-August) Post-season (Collected in January-February)	Pre-season (453) Post-season (565)	Pre-season (277) Post-season (289)
Playing Position	All playing positions were allocated into four main groups	Defence (317) Forward (208) Goalkeeper (110) Midfield (383)	Defence (200) Forward (84) Goalkeeper (59) Midfield (223)
Squad	The age-group that players were in during the time of testing.	U12 (83) U13 (114) U14 (114)	U12 (38) U13 (49) U14 (54)

		U15 (119)	U15 (80)
		U16 (120)	U16 (84)
		U17 (125)	U17 (79)
		U19 (133)	U19 (102)
		U23 (125)	U23 (77)
		1st (85)	1st (3)
Gender	Male	1018	566
Precued Choice Reaction Time Task	Response Time (s)	505	329
Vienna Test System:	Number of Correct Answers (#)	987	545
Determination Test	Response Time (s)	974	538
Vienna Test System: Response	SSRT (s)	961	536
Inhibition	Reaction Time (s)	917	516
Helix (Multiple Object Tracking Task)	Number of Correct Answers (#)	531	313

Supplementary Table 2. Detailed description of the statistical process undertaken to achieve the best fitting model.

Statistical Process	
Overview	To investigate the effect of age (decimal age at the time of testing), years of playing experience in football and playing position (grouped into: forwards, midfielders, defenders and goalkeepers), a series of mixed linear models were developed where the individual player's intercepts were varied randomly to account for repeated measures on a series of executive function assessments. To construct each mixed model, a stepwise approach was used, in which additional predictors were added to the model with each step, and model fit was observed. How well a developed model fitted the observations was evaluated using Akaike's An Information Criterion (AIC), an inspection of the degrees of freedom and the significance of the introduction of predictor variables into the models using a second order polynomial. The significance level for the 2nd order polynomial tests was set at $p<0.05$.
Testing model assumptions	The first step to the construction of the mixed model was to perform the pre-modeling assumption check for multicollinearity and the linearity of the relationship between predictors and the response variable. Due to a high multicollinearity between the predictor variables 'Age' and 'Years of Playing Experience' (i.e. where older players also have more years of playing football and therefore are not independent of each other), two individual analyses were conducted in order to remove any inflation caused by collinearity between the two predictor variables.

Step-up approach to constructing mixed linear models	First, a 'hypothesis-testing' null model was developed that allows for random intercepts for different players (to account for the random variance associated with players' repeated measures), which could confound the potential relationship between the predictor variables and executive function performance. This null-model was then used to investigate the significance of each added predictor through investigating the goodness-of-fit indices such as the AIC and the p-value of a new test relative to the added complexity of the model (through added degrees of freedom).
Post-modeling mixed model assumptions	Upon constructing different linear mixed models, these models needed to undergo post-modeling assumptions checks. The main checks used in this study were: the normal distribution of model residuals through visual analysis of the QQ-plots of the model residuals and a Shapiro-Wilks test of normality.
Log-transformation	Given that the models' residuals were not normally distributed, the response variables (executive function measurements) were log-transformed. The log-transformed variables were used to replace the previous (non-logged) response variables in the models. However, upon repeating the previous steps with the logged response variables, the log transformation did not improve the model fit with respect to the models with the non-logged response variables.
2nd Order polynomial model	Scatterplots revealed that the data from the executive function measurements was negatively accelerated and not linear, meaning that larger increases in performance

	occur early on in age and years of experience of the player, and then plateau later on in older adults. Therefore, a second order polynomial appeared to be the best fit for the data compared to the other aforementioned models.
Develop 2nd order polynomial models	Given that 2nd order polynomial models were the best fit for the data, these transformed variables were retained and used to replace the response variables in the previously create models.
*Introduce Age/Experience*Position interaction effects*	Decimal age*playing position and experience*playing position interaction effects were introduced to determine if the effect of age or playing experience could be dependent on a player's field position.
Post modeling checks on model with transformed response variables	Once more, the models that retained the 2nd order polynomial transformed data underwent post modeling assumption checks. A visual analysis of the QQ-plots for the best fitting models' residuals were performed.
Generate model outputs	Once the models were deemed appropriate, each model's explained variance associated with only the fixed effects or the fixed and random effects combined, 95% confidence intervals obtained using the Wald method, the observed effects of random and fixed predictors, the model coefficients and least-square means obtained from each model were obtained as model outputs.

Chapter 4: The Footbonaut as a new football-specific skills test: reproducibility and age-related differences in highly trained youth players.

The content has been reformatted for the purposes of this thesis. The full reference details of the published manuscript are:

Beavan, A., Fransen, J., Spielmann, J., Mayer, J., Skorski, S., & Meyer, T. (2019). The Footbonaut as a new football-specific skills test: reproducibility and age-related differences in highly trained youth players. *Science and Medicine in Football*, 3(3), 177-182.

4.1 Abstract

Introduction: In sport, performance assessments are routinely administered to give an indication of performance, normally across various time points. In order to assess a skill, external factors must dictate how and when the action is performed, highlighting the need for skill assessments to closely replicate the perception-action couplings experienced in football game play. Therefore, this study aimed to investigate if the Footbonaut is a valid and reliable football-specific skill assessment tool. **Methods:** Footbonaut performance scores from 152 male players from U12 to U23 representing a professional German Bundesliga club during the pre-season/ early in-season 2016/17 season were analysed. **Results:** Pearson correlations (r) and coefficient of variation (CV) for the correct number of passes in a target (CV = 7.5-11.1; r = 0.48; p<0.001), the speed at which they completed each trial (CV = 2.6-5.1; r = 0.70; p<0.001), and a computer-generated point score (CV = 7.4-12.3; r = 0.77; p<0.001) demonstrated acceptable test-retest reliability. Moreover, a MANOVA revealed a strong multivariate effect of age group on speed and accuracy combined (F = 7.80, p<0.001, ES = 0.28), demonstrating the Footbonaut's construct validity. **Conclusion:** In conclusion, the results in this study demonstrated that the Footbonaut is a valid and reliable assessment of football-specific skill.

Keywords: Passing, perceptual-cognitive skill, reliability, validity, representative design

4.2 Introduction

Football (Association Football) is a dynamic sport that requires players to utilise a highly automatic yet complex cohesion of physical fitness, football-specific motor skill, and perceptual-cognitive skill (Ali, 2011). Many attempts have been made to capture football performance as a whole through a battery of laboratory and on-field assessments. When specifically assessing skill performance, it has been common practice to separate one aspect of the game such as dribbling performance (i.e. dribbling a ball around a pre-set course marked with cones) (Aquino et al., 2016) or ball control (i.e. playing six passes alternately against two opposing impact walls with at least two ball contacts) (Leyhr et al., 2018). Many talent identification programs use unique combinations of isolated tests to evaluate youth players' football performance, such as the Ghent Youth Soccer Project (Vaeyens et al., 2006). The combined results of the assessment batteries are routinely used for talent selection purposes, to compare changes in performance to normal baseline measures or to examine the effectiveness of a training regime (Serpiello et al., 2017). Although there are closed skills in football such as free kicks, football is predominately a dynamic environment in which players find functional movement solutions to movement problems that occur in constantly changing environments. Isolating a single aspect of the game should be considered a measure of technical ability rather than a demonstration of skill (Strand & Wilson, 1993).

The design of a new assessment of football-specific skill is challenging due to the complex relationship of many physical and perceptual determinants of playing ability (Williams, 2000). In order to assess football-specific skill, the test must allow for external factors to dictate how and when the actions are performed, in a dynamic and unpredictable context (Krause et al., 2018). However, a major barrier in the design of any skill assessment that aims to replicate the requirements of real-world environments is to provide the player with the optimal amount of uncertainty that mirrors game conditions, yet includes enough precision in the protocol to allow for test reliability (Ali, 2011).

The most common performance assessment of skill is passing ability. Passing is an essential aspect of football, as it has been previously reported that a short pass preceded 47% of goals scored by direct shots in the 2006 FIFA World Cup (Sajadi & Rahnama, 2007). Many researchers have devised tests to examine passing ability such as the Loughborough Soccer Passing Test (LSPT) (Ali et al., 2007) or the physical and technical test (PT-test) (Rostgaard, Iaia, Simonsen, & Bangsbo, 2008). Although these assessments have obvious merit to examine technical abilities, the LSPT was reported to not be representative of in-game passing performance (Serpiello et al., 2017). This may be the result of its uni-dimensional task constraints with no manipulation of task performance.

Thus, there is still a paucity of literature related to football-specific skill assessments that more closely mirror the constraints players encounter during in-game performance. The Footbonaut (CGoal GmbH, Berlin, Germany) is a relatively new training and assessment tool developed in 2013. The unique design of the Footbonaut allows for the serial coupling between perception and action with the addition of unpredictability allowing for a better measurement of skill than that of previous assessments. A player in the Footbonaut can undergo an individualised training session to improve their skills, such as training their weaker foot's passing performance and first touch. Moreover, each player can be assessed on a standardized protocol to allow staff to monitor an individual's performance throughout the season, analyse between or within-group comparisons, and create age-group norms for talent identification purposes. Performance in the Footbonaut is measured by a combination of the accuracy of the pass, and the speed at which the player carries out this movement in each trial. See Figure 4 for a schematic drawing of the Footbonaut.

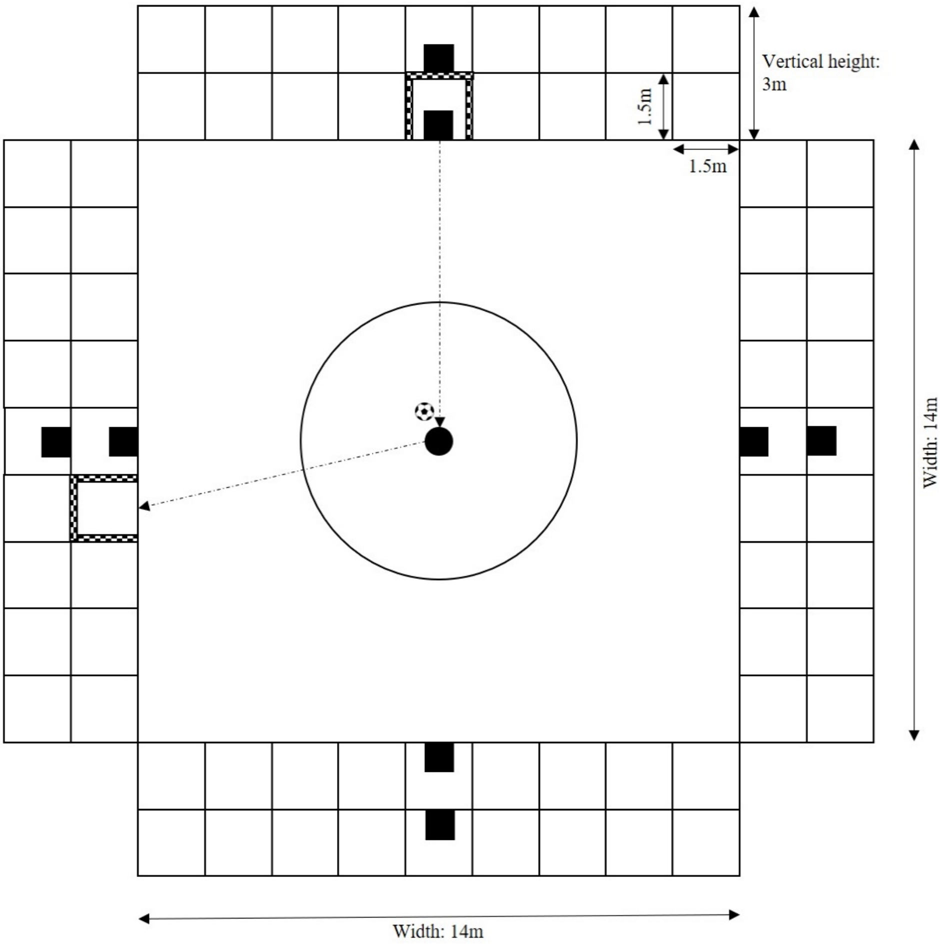


Figure 4. A schematic drawing on the Footbonaut.

Practitioners and scientists alike depend on the results of an assessment task to be a meaningful and a true representation of performance. Thus, discriminant validity and reproducibility of the Footbonaut are a necessary prerequisite for its further implementation as an assessment tool. The aims of the present study were twofold: 1) to assess the test-retest reliability of the Footbonaut and 2) to assess its discriminant validity by investigating the influence of age and football experience on test performance. It was hypothesised that the Footbonaut is a reliable assessment instrument and that older players would perform better in the Footbonaut compared to younger players.

4.3 Materials and methods

4.3.1 Participants

Retrospective data on male youth football players in eight age groups: U12 (n =18), U13 (n = 20), U14 (n = 18), U15 (n = 20), U16 (n = 20), U17 (n = 8), U19 (n = 25), and U23 (n = 23) representing a professional German Bundesliga club during the pre-season/ in-season of 2016/17 were analysed. Each age group played at the highest level for their region and age. All participants (and parents for players under 18 years of age) signed contracts confirming that data arising as a condition of player monitoring over the course of the competitive season can be used for scientific purposes (Winter & Maughan, 2009). The Faculty of Empirical Human Sciences and Economics ethics committee of Saarland University reviewed and approved this study.

4.3.2 Skill test design

The Footbonaut is designed to be a realistic training tool that mirrors the dynamic elements of football gameplay by incorporating both physical (dribbling, passing, and shooting) and perceptual-cognitive (information-processing from auditory and visual cues) components. The Footbonaut consists of a 14 x 14 m artificial turf surface (Morton Extrusionstechnik GmbH, Absteinach, Germany) and is surrounded by four walls. Together, these walls consist of 72 positioned square panels (64 target gates and 8 ball dispenser gates each 1.5 x 1.5 m, with two horizontal rows of gates per wall). Each gate is equipped with light barriers around the perimeter and light-emitting diodes (LEDs) to measure the ball exiting and entering gates.

4.3.3 Procedure

Each age group was assessed on separate days but followed a standardized procedure. Players did not conduct any physical training the morning of the assessment. Players entered the Footbonaut and started the session in the centre zone. Before commencing the test, players had a practice session consisting of 10 trials to familiarize themselves with the equipment. Players received the instruction to 'perform the assessment as fast and accurate as possible'. Each session consisted of a standardized combination of 32 consecutive balls (see Table 5). A countdown of four seconds preceded the commencement of the test. Within each trial, an auditory and visual cue informed the participant which specific gate the ball would be dispensed from, and a second auditory and visual cue immediately identified the location of the target gate the player had to pass the ball into. The visual cue for the ball dispenser gate was a red light illuminated along the perimeter of the panel. The visual cue for the target was a green light illuminated around the perimeter of the specific target gate. If the player did not pass the ball into the target after two seconds of the ball being dispensed, the target light would change colour to blue. After five seconds the light would change colour to white, and the trial outcome was considered to have resulted in 'no goal'. After the ball entered through a gate, the player had to swiftly return to the middle of the test zone to receive the next ball. The athletes performed two sessions on the same day separated by a 15-minute resting period. No verbal encouragement during the session was given, nor were players told how many balls remained at any point. Upon completion of each session, players were provided with knowledge of results (accuracy and speed) (see Table 5).

Table 5. The parameters and performance variables defined for each session in the Footbonaut.

Parameter	**Value**	**Description**
Balls	32	Number of balls dispensed
Ball Dispenser Power	50 km/hr	Speed of the ball
Vertical Angle	2^{o}	Angle of inclination of ball-dispenser
Shot Delay	800 ms	Delay between when the auditory cue and the ball dispensed
Gates Used	360^{o}	$360^{o}/360^{o}$ gates used
Variables	**Value**	**Description**
Accuracy	Percentage (%)	Correct number of passes through the gates
Speed	Seconds (s)	Time the ball is dispensed until it enters the gate
Points	Arbitrary Unit (Au)	An algorithm comprised of accuracy, speed and location of gates in reference to the ball dispense

Note: Only the bottom row gates and ball dispensers were used.

4.3.4 Statistical analyses

Kolmogorov-Smirnov normality tests alongside visual inspections of data using boxplots and histograms were used to examine if the speed, accuracy and points from both sessions followed a normal distribution in the entire sample. Collectively, it was deemed that these variables were normally distributed and therefore warranted the use of parametric statistics.

Pearson's correlation (r) and the coefficient of variation (CV) were used to assess test-retest reliability for speed, accuracy, and points for the entire sample. The interpretation of the Pearson's correlation coefficients followed the guidelines by Evans (1996), where correlations between .00-.19, .20-.39, .40-.59, .60-.79 and .80-100 are considered very weak, weak, moderate, strong and very strong respectively. Furthermore, discriminant validity of the Footbonaut was assessed by examining changes in speed, accuracy, and points based on age groups. Therefore, a Multivariate Analysis of Variance (MANOVA) was used to assess the effect of age on Footbonaut performance using the age group that the players belonged to (U12-U23) as a fixed factor and the speed and accuracy variables generated by the Footbonaut as dependent variables. As the variable 'points' are calculated using an algorithm that includes speed and accuracy components among other factors such as the spin of the ball and the location of the ball release in regard to target location, a separate Analysis of Variance (ANOVA) with points as the dependent variable and age group as a fixed factor was used to analyse between group differences in points. Bonferroni corrections were used to investigate multiple comparisons between age groups and partial eta squared effect sizes were used throughout to investigate the magnitude of any observed effects using Cohen (1988) guidelines for interpreting effect sizes: 0.01-0.06 = small effect, 0.06-0.14 = moderate effect and >0.14 = large effect.

Finally, as the Footbonaut is a commercially available tool and the algorithm related to the calculation of the Footbonaut point score is not readily available, a linear regression with points as the dependent and speed and accuracy as independent variables was used to analyse the variance in the points that can be attributed to a player's accuracy and speed. For all analyses, the significance level was set at $p < 0.05$.

4.4 Results

Pearson correlations (r) revealed moderate to strong relationships between the test and retest scores for the entire sample, and the dispersion measured through CV values was adequate and comparable to previous tests of football skill for all age groups (Ali et al., 2007) (see Figure 5). More specifically, accuracy (CVmean = 8.68; $r = 0.48$; $p < 0.001$), speed (CVmean = 3.60; $r = 0.70$; $p < 0.001$), and points (CVmean = 8.93; $r = 0.77$; $p < 0.001$) demonstrated acceptable test-retest reliability.

A MANOVA revealed a strong multivariate effect of age group on speed and accuracy combined ($F = 7.80$, $p < 0.001$, ES = 0.28). Further univariate analysis revealed strong age group effects on speed ($F = 14.88$, $p < 0.001$, ES = 0.42) and accuracy ($F = 3.77$, $p = 0.001$, ES = 0.16) components of players' Footbonaut performance. More specifically, U19 and U23 players were more accurate than U12 players, and speed decreased with increasing age in the youngest cohort of players (U12-U14), but no more differences in speed were observed between players in the U15-U23 categories (see Table 6). Additionally, the ANOVA revealed strong age group effects on points ($F = 17.96$, $p < 0.001$, ES = 0.47) in which a similar trend was observed for the effect of age group on speed.

Finally, a multiple regression analysis showed that 88 percent of the variance ($F = 539.10$, $p < 0.001$) was explained by speed and accuracy components. Both speed and accuracy were significant predictors of points, but speed seemed to be a bigger contributor (beta = -0.75) than accuracy (beta = 0.38). The regression equation derived from this multiple regression is: 142902 + 469.73*Accuracy(%) – 49981*Speed(s). Confidence intervals for the constant and these coefficients are 130678.24 - 155126.51, 396.80 - 542.66, and -53922.95 - -46039.39 respectively.

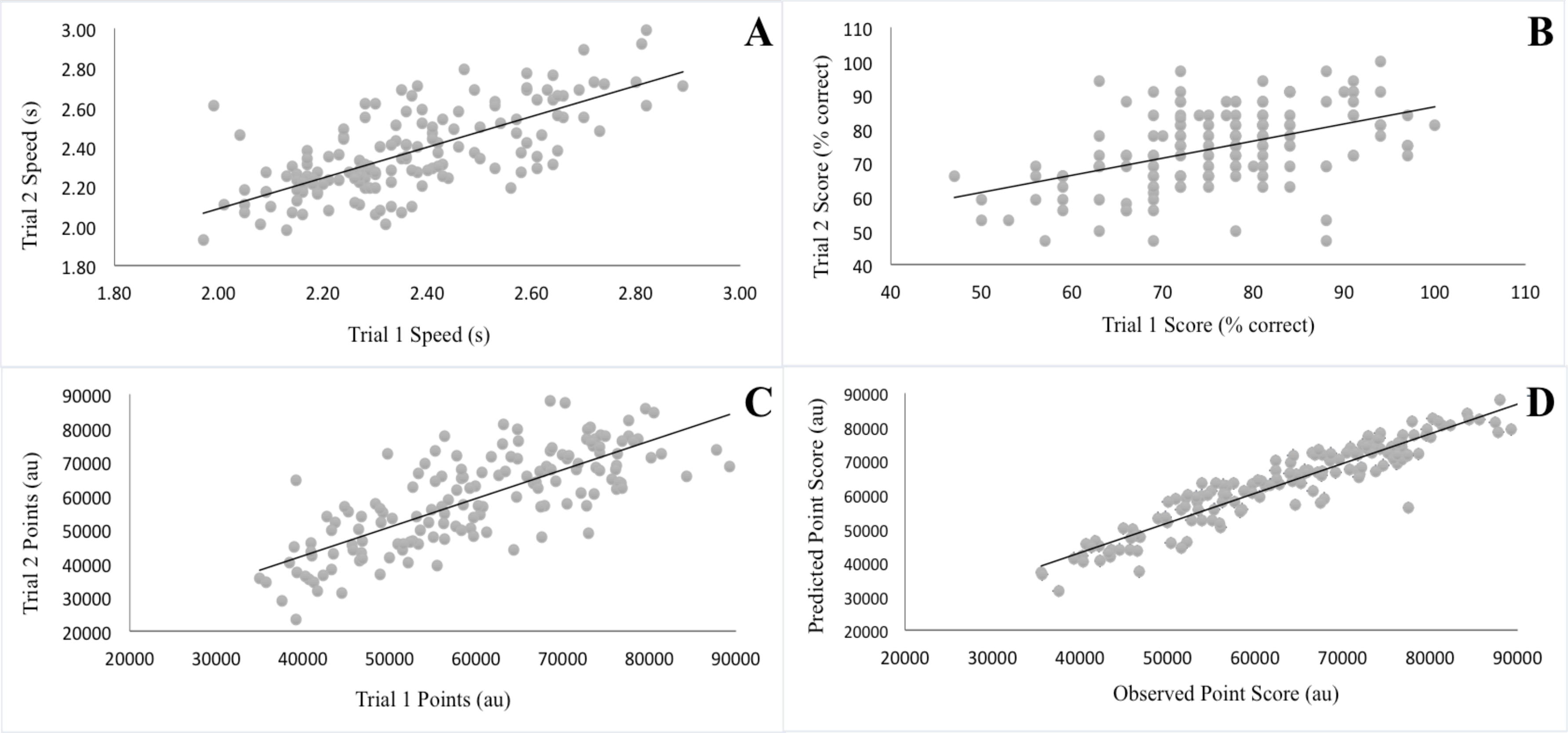


Figure 5. A-C: scatterplots demonstrating test-retest reliability for speed, accuracy and points components of U12-U23 players' Footbonaut performance. D: predicted versus observed scores for a multiple regression analysis in which points are predicted by speed and accuracy of U12-U23 football players' Footbonaut performance.

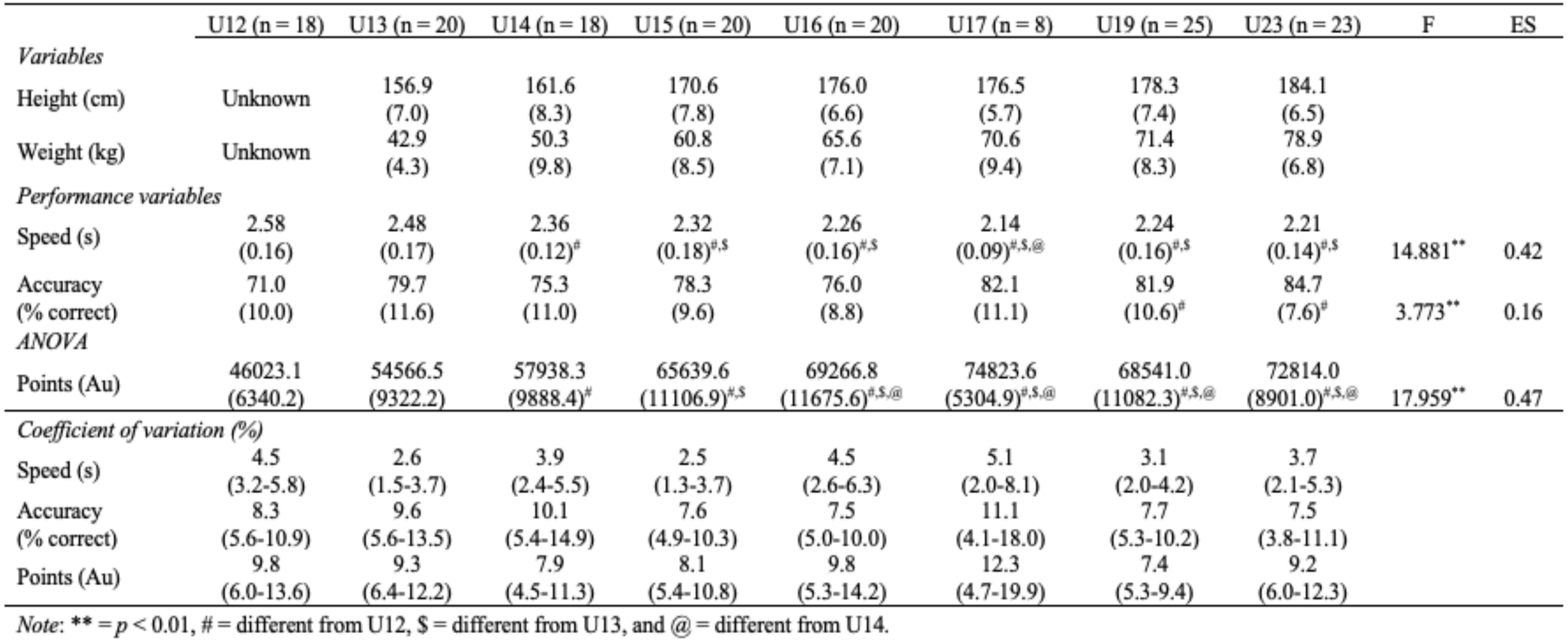
4.5 Discussion

The main findings of this study were that the Footbonaut is a reliable tool across all age groups and some discriminant validity was observed through performance differences between younger and older age cohorts in this study. The results confirmed the hypothesis that older players performed better in the Footbonaut compared to their relatively younger counterparts; however, the age performance differences were less pronounced in accuracy in comparison to speed and points.

The Footbonaut is a relatively new tool allowing athletes to be assessed in a standardized and representative football environment that more closely replicates the serial coupling of perception and action experienced during football match play. Results revealed moderate to strong relationships between test and retest scores for the entire sample of players. According to previous research in football, a strong relationship exists between accumulated sport specific practice and better performances on assessments of technical and tactical skills (Hendry, Williams, & Hodges, 2018). Therefore, it was hypothesised that there would be a positive linear relationship between age and Footbonaut performance. Although each performance variable demonstrated trends of improvement with incremental increases in age, there were no other significant differences observed between players in the U15-U23 categories. Thus, the discriminant validity of the Footbonaut disappears when groups become more homogeneous after the age of 15 years.

The observed plateau of skill differences after the age of 15 reported in this study are in line with recent research on the development of skill in youth football players. A recent study that analysed three years of athletic development of highly talented young football players in the German Football Association’s talent identification program reported that substantial improvements in participants’ performance in motor skill assessments occurred from U12-U15 (Leyhr et al., 2018). The progression was non-linear, where players’ motor performance increased considerably from U12 to U13 and became less prominent in subsequent years (i.e. from U13-U14 and U14-U15). The results of this study are also in line with Huijgen (2013) reporting that players’ dribbling performance improved largely between U13-U15 followed by a phase of development plateau after the U15 age group.

Table 6. The performance variables mean (*SD*), F-values, significance levels and partial eta squared effect sizes (ES) between age groups for best speed, best score and best points out of two trials. Furthermore, the reliability measures (coefficient of variation ± 95% CI) from each age group.



	U12 (n = 18)	U13 (n = 20)	U14 (n = 18)	U15 (n = 20)	U16 (n = 20)	U17 (n = 8)	U19 (n = 25)	U23 (n = 23)	F	ES
Variables										
Height (cm)	Unknown	156.9 (7.0)	161.6 (8.3)	170.6 (7.8)	176.0 (6.6)	176.5 (5.7)	178.3 (7.4)	184.1 (6.5)		
Weight (kg)	Unknown	42.9 (4.3)	50.3 (9.8)	60.8 (8.5)	65.6 (7.1)	70.6 (9.4)	71.4 (8.3)	78.9 (6.8)		
Performance variables										
Speed (s)	2.58 (0.16)	2.48 (0.17)	2.36 (0.12)$^{\#}$	2.32 (0.18)$^{\#,\$}$	2.26 (0.16)$^{\#,\$}$	2.14 (0.09)$^{\#,\$,@}$	2.24 (0.16)$^{\#,\$}$	2.21 (0.14)$^{\#,\$}$	14.881**	0.42
Accuracy (% correct)	71.0 (10.0)	79.7 (11.6)	75.3 (11.0)	78.3 (9.6)	76.0 (8.8)	82.1 (11.1)	81.9 (10.6)$^{\#}$	84.7 (7.6)$^{\#}$	3.773**	0.16
ANOVA										
Points (Au)	46023.1 (6340.2)	54566.5 (9322.2)	57938.3 (9888.4)$^{\#}$	65639.6 (11106.9)$^{\#,\$}$	69266.8 (11675.6)$^{\#,\$,@}$	74823.6 (5304.9)$^{\#,\$,@}$	68541.0 (11082.3)$^{\#,\$,@}$	72814.0 (8901.0)$^{\#,\$,@}$	17.959**	0.47
Coefficient of variation (%)										
Speed (s)	4.5 (3.2-5.8)	2.6 (1.5-3.7)	3.9 (2.4-5.5)	2.5 (1.3-3.7)	4.5 (2.6-6.3)	5.1 (2.0-8.1)	3.1 (2.0-4.2)	3.7 (2.1-5.3)		
Accuracy (% correct)	8.3 (5.6-10.9)	9.6 (5.6-13.5)	10.1 (5.4-14.9)	7.6 (4.9-10.3)	7.5 (5.0-10.0)	11.1 (4.1-18.0)	7.7 (5.3-10.2)	7.5 (3.8-11.1)		
Points (Au)	9.8 (6.0-13.6)	9.3 (6.4-12.2)	7.9 (4.5-11.3)	8.1 (5.4-10.8)	9.8 (5.3-14.2)	12.3 (4.7-19.9)	7.4 (5.3-9.4)	9.2 (6.0-12.3)		

Note: ** = $p < 0.01$, # = different from U12, $ = different from U13, and @ = different from U14.

Another recent study noted that it may be between 15-17 years old that skill refinement is significant during youth development, and where perceptual-cognitive skills begin to become more apparent (Hendry et al., 2018). Accordingly, a common theme shared amongst the current study and previously used testing protocols is that they may not have been challenging or sensitive enough to measure any further developments in perceptual-cognitive skills after the age of 15. If technical skills begin to plateau after the age of 15, then alternative approaches may be to develop more age-appropriate test protocols that place greater demands on the perceptual-cognitive component in older cohorts. For example, Fransen et al. (2017) manipulated the perceptual-cognitive component in a football-specific dribbling task by restricting visual feedback with stroboscopic glasses. Similar concepts may strengthen the discriminant validity of the Footbonaut in older age groups. However, any adjustment to the standard protocol used in this test would require further evaluation (McDermott, Burnett, & Robertson, 2015). Additionally, as many of the findings in previous research are attributed to maturational changes in individuals during early adolescence (Huijgen, Elferink-Gemser, Post, & Visscher, 2010; Leyhr et al., 2018; Malina, Ribeiro, Aroso, & Cumming, 2007), future research should also consider measuring the influence that physical and cognitive maturation has on performance in the Footbonaut.

Despite the numerous advantages of using the Footbonaut, a number of limitations should be considered when interpreting the results of the present study. First, the Footbonaut is an expensive tool (estimated USD $3.5 million) that is not widely available or accessible for the majority of football clubs. Thus, the development of a more affordable skills assessment test that mirrors the reciprocal relationship between domain-specific and perceptual-cognitive skills of the Footbonaut has value. Second, unlike the LSPT, the Footbonaut cannot distinguish between gross and fine motor performance in the session, and where the errors lie in a slower test completion time. Future research should incorporate the analysis of video footage within the Footbonaut to measure performance aspects like the ‘first touch’. Lastly, it is not clear what performance variables are most beneficial to performance in the Footbonaut. For instance, it is not evident whether older groups are physically better with similar perceptual-cognitive abilities as the younger groups, or that older players are superior at planning their executions of movements from better perceptual-cognitive skill. To overcome this limitation, future research should explore the cofounding effects of perceptual-cognitive skills (i.e. visual scanning behaviour prior to receiving the ball (McGuckian, Cole, Chalkley, Jordet, & Pepping, 2018a)) and physical fitness (i.e. speed and agility) on performance in the Footbonaut. Thus, the addition of isolated tests of domain-specific skills may compliment the Footbonaut within a battery of tests to provide further insight into what strengths and weakness' in performance a player yield.

4.6 Conclusion

The results demonstrated that the Footbonaut is a reliable and valid tool to differentiate between age groups in youth male football players but has stronger discriminant validity in cohorts below U15. More research is needed to investigate which parameters of performance can be added to the Footbonaut to improve the discriminant validity between older age groups in youth football. Furthermore, practitioners should be aware of the limitations of using skill tests that isolate single aspects of the football such as measuring dribbling performance using a ball around pre-set cones, as such tests might not be representative of in-game performance. Therefore, representative assessments of football-specific skill should involve a combination of both physical and perceptual-cognitive components.

4.7 Practical implications

The Footbonaut is a tool with the potential to open new avenues for using representative research designs that can further understanding of the reciprocal nature of the perception-action coupling in football. The findings of this study are valuable for practitioners who want to design representative tasks, as the Footbonaut can be replicated in the field by coupling passing actions with decision making and measuring speed and accuracy.

Chapter 5: A Longitudinal Analysis of the Executive Functions in High-Level Football Players

The content has been reformatted for the purposes of this thesis. The full reference details of the published manuscript are:

Beavan, A., Chin, V., Spielmann, J., Mayer, J., Skorski, S., Meyer, T., & Fransen, J. (in press). A longitudinal analysis of the executive functions in high-level football players. *Journal of Sport & Exercise Psychology.*

5.1 Abstract

Introduction: Assessments of executive functions (EFs) with varying levels of perceptual information or action fidelity are common talent diagnostic tools in football. Yet, their validity still has to be established. Therefore, a longitudinal development of EFs in high-level players to understand their relationship with increased exposure to training is required. **Methods:** 304 high-performing male youth football players (10-21 years old) in Germany were assessed across three seasons on various sport and non-sport specific cognitive functioning assessments. **Results:** Posterior means (90% highest posterior density) of random slopes indicated that both abilities predominantly developed between 10-15 years old. A plateau was apparent for domain-specific abilities during adolescence, whereas domain-generic abilities improved into young adulthood. **Conclusion:** The developmental trajectories of football players' EFs follow the general populations', despite long-term exposure to football-specific training and gameplay. This questions the relationship between high-level experience and EFs and renders including EFs in talent identification questionable.

Keywords: Domain-General, Bayesian inference, football, representative design, talent identification

5.2 Introduction

Throughout the cognitive maturation process into adulthood, children playing sport progressively develop the ability to "read the game", process the surrounding environment, and learn from previous errors. Furthermore, older athletes are better to engage in goal-directed thought and action while negating acting on impulsive decisions, and can be attributed to the simultaneous development of cognitive control functions such as working memory, inhibition, and flexibility (Diamond & Lee, 2011). These three cognitive abilities are known as core executive functions (EFs), a type of high-order functioning, which forms the foundation that other cognitive processes such as problem-solving, reasoning and planning are built upon (Diamond, 2013).

EFs are a consciously controlled process that engages in deliberate, goal-directed thought and action (Zelazo et al., 2004), and play a role in the decision-making process (Best & Miller, 2010; Furley & Wood, 2016). EFs yield a high face validity in sports, as they seemingly reflect the higher-order cognitive functioning required when athletes interact with their match environment (Jacobson & Matthaeus, 2014). Supporting this proposition, the first meta-analysis to examine the link between EFs and expertise in sport reported that athletes performed better on measures of processing speed, most notably amongst those playing interceptive sports such as tennis, fencing and boxing (Voss et al., 2010). Currently however, there is a lack of agreement in the literature on the relationship between EFs and sporting expertise. On one hand, a recent meta-analysis on football-specific populations reported that high-performing athletes possess better EFs compared to lower-level and non-sporting populations (Scharfen & Memmert, 2019). On the other hand, additional research did not confirm the generalization of better EFs linked with expertise, where no discrepancies between different levels of expertise in tennis (Kida et al., 2005), ice hockey (Lundgren et al., 2016), or basketball (Nakamoto & Mori, 2008) were reported. These indifferences may be attributed to the nature of the task design, being that EF assessments generally present non-sport-specific information, which in turn limits the athletic superiority (Wang et al., 2015; Wang & Tu, 2017).

Ericsson’s leading view on expertise supports that cognitive superiority is specific to an athlete’s domain, and therefore high and low-level athletes, and non-athletic populations should only differ in the cognitive processes that are related to the specific sport processes (i.e. domain-specific abilities) (Ericsson, 2014; Ericsson et al., 2018). Opposingly, “basic” cognitive abilities (i.e. domain-generic abilities), such as EFs, does not contribute to expertise, and therefore variability in generic abilities should have no observable influences on performance (Ericsson et al., 2018). However, a review by Macnamara, Hambrick, and Oswald (2018) on expertise reports that only 18% of the variance in sporting performance can be explained by the accumulated hours of engagement in structured activities related to improving performance, resulting in a substantially weaker relationship than Ericsson argues. Thus, investigating the role of domain-generic abilities alongside the attainment of expertise may yield a valuable contribution towards the large (82%) unaccounted variance (Macnamara et al., 2018).

Further, one significant limitation within the sporting literature is that previous examinations of EFs throughout the development of athletes have been cross-sectional and longitudinal studies in athletic populations are lacking, limiting the generalizability of existing longitudinal EFs studies from general to athletic populations. To date, a considerable amount of longitudinal studies has mapped out the developmental trajectories of EFs in the general population (Howard, Vella, & Cliff, 2018; Huizinga & Smidts, 2010; Zelazo & Carlson, 2012; Zelazo et al., 2004). Age-related improvements in EFs occur rapidly from late childhood into adolescence and continue to improve into young-adulthood, albeit at a slower rate (Huizinga et al., 2006; Zelazo & Müller, 2002). Indeed, many studies using various neuropsychological tasks reported similar findings demonstrating that adult levels of performance on such tasks is attained between the ages of 12-15 (Diamond, 2002; Huizinga et al., 2006). Importantly, cognitive maturation allows for a more refined ability to use the same EFs that are present in children rather than the emergence of new cognitive processes (Engelhardt, Harden, Tucker-Drob, & Church, 2019; Luna, 2009). This maturation process strengthens the ability to perform more complex tasks, differentiate between task-relevant and task-irrelevant stimuli, and maintain attention for longer, amongst many other benefits (Engelhardt et al., 2019).

Currently, domain-specific and domain-generic abilities have been independently examined, leaving their relationship across the development of expertise uncertain. Furley and Wood (2016) advocated that longitudinal studies that assess both domain-specific and domain-generic abilities to explain sporting expertise are needed to demonstrate the acquisition of both abilities across the critical developmental periods. Therefore, the purpose of the present study was to document age-related changes in both domain-specific (i.e. assessments that present either football specific information, or require football-specific action to a certain degree) and domain-generic (i.e. assessments that neither represent football-specific information nor require football-specific action) abilities in a longitudinal manner. This will probe and expand the available body of research on the acquisition of these abilities and how they are affected by increasing football experience. It is expected that with age, and hence increased exposure to high-level football training, high-level athletes' domain-generic developmental curves will reflect those of individuals from a general population and reach near maturity around adolescence. Contrastingly, as domain-specific cognitive functioning is more influenced by the environment and experience of an individual within a specific domain, it is hypothesized that performances on football-specific assessments will continue to develop with age.

5.3 Methods

5.3.1 Participants

The dataset comprised of 304 male football players aged between 10 to 21 years old representing a professional club in Germany's 1st division. This sample is a convenience sample, being that it consists of only players representing one professional club. All players included in this sample played at the highest level of competition for their age-group and region. Players below 21 years of age that conducted the testing battery at a minimum of one time were retained in the analysis. Players > 21 years old (between 22-37 years, n = 42 individual players) were excluded from the study due to the low density of the sample for each age cohort not allowing for a reliable inference on the model parameters (i.e. rate of growth) to be made. The subjects were grouped according to their playing position, with each classified as a forward (65), midfielder (109), defender (98) or goalkeeper (32). Across this age range, the development of EFs was broken down into four different developmental stages: late childhood (10–12 years old), pre-adolescence (12–15 years old), adolescence (15–18 years old) and early adulthood (18–21 years old), aligned with the developmental stages described by Côté and Vierimaa (2014). Prior to the commencement of this study, informed consent and assent for all players was received, and the Institutional Ethics Committee approved this study. The number of observations per measurement variable collected from the assessment battery can be found in Supplementary Table 3, whereas an examination of the distribution of players according to the developmental stage of EFs that they were in at the time of testing can be found in Supplementary Table 4.

5.3.2 Procedures and apparatus

Data were collected from the 2016/17 to the 2018/19 season. Players participated in a battery of assessments aimed at measuring higher level cognitive functioning twice-yearly, once during pre-season (July-August) and around the winter break (January-February). The order in which the assessments were conducted was randomized. Standardized instructions were programmed into each assessment, and a staff member remained in the room to further help clarify any questions. Each assessment had a standardized familiarization protocol prior to commencing the experimental trials. The players completed four individual cognitive assessments. The methodology used below is a replication of the methodologies adopted by Beavan and colleagues (Beavan et al., 2018; Beavan et al., 2020).

5.3.2.1 Assessments that present domain-generic perceptual information and require a domain-generic action

5.3.2.1.1 Reactive stress tolerance task

The Determination Test (Schufried GmbH, Austria) is a complex multi-stimuli reaction assessment involving the combination of five different coloured stimuli and two acoustic signals (2000 Hz high and 100 Hz low tone) for finger pressing, and two pedal stimuli for the feet. These stimuli corresponded to the pressing of appropriate buttons on the response panel and foot pedals. The determination test aims to measure reactive stress tolerance and the associated reaction speed. The participant must remain composed whilst the quick succession of the single pairing of stimulus and response lasting four minutes. ‘Correct responses' describes the total number of accurate responses within the four minutes, and 'response time' is the median response time (s) from the appearance of a stimulus to pressing of the correct button. The validity and reliability of the Vienna Test System has been confirmed by a variety of studies (Schuhfried, 2001; Whiteside et al., 2003) and been previously been used in high-level football players (Beavan et al., 2019).

5.3.2.1.2 Stop signal task

The response inhibition test (Schufried GmbH, Austria) uses a stop signal paradigm. In each trial, the player is presented with an arrow either pointing left or right, to which he must respond by pressing the corresponding button. Each arrow is displayed for one second, and the time before the subsequent arrow appears is also one second. Seventy-six stimuli are 'go trials', with the other 24 stimuli having a tone at a pitch of 1000 Hz for 100 ms (stop signal). The player must then suppress the already initiated response, known as 'stop trials'. The time between the presentation of the stimulus and the tone is dependent on the player's performance (recorded as the mean reaction time in seconds) being that if the player responds correctly to a stop signal trial, the interval for the next stop stimuli will occur 50 ms later, and vice versa. Therefore, the correct response to the stimuli will continually progress in difficulty (minimum 50 ms; maximum 350 ms). The dependent variable that reflects the latency of the inhibitory process is stop signal reaction time (SSRT). The SSRT is calculated by deducting the mean stop signal delay from the mean reaction time (s).

5.3.2.1.3 Precued choice response time task

Participants were required to press the button on a joystick panel associated with a stimulus circle presented on the laptop screen as fast and accurate as possible. The Precued Choice Response Time Task (PCRTT) was developed using Unity software (Unity, Version 5.4.0f3, 2016). Four blank stimulus circles were presented in a horizontal line, with one circle turning yellow in colour after a randomized (2-4 second) fore-period length. Each circle had a diameter of 512 pixels and an edge width of 5 pixels on a 13.2-inch display. Prior to the appearance of the stimulus, a three second countdown timer was shown. After the appearance of the four stimulus circles, a small dot appeared for 43 ms in the centre of one stimulus circle, 86 ms prior to the circle turning yellow. 24 trials were conducted. 12 trials had the small dot appear in the same circle as the yellow dot (congruent) and the other 12 trials had the dot appear in a different circle to the yellow dot (incongruent). Response time (ms) was measured as the duration between the appearance of the stimulus circle (turned yellow) on the computer screen and the moment the button was pressed by the participant. Three variables are derived from this assessment: i) response time to only the congruent trials, ii) response time to only the incongruent trials, and iii) response inhibition being the sum of the response times to congruent minus the sum of the response times to incongruent trials. This assessment has been previously used as a measure of perceptual-cognitive functioning in both general (Barela et al., 2019) and high-level athletic populations between youth and adults (Beavan et al., 2019), highlighting its use as measure of EF.

5.3.2.2 Assessments that present domain-specific perceptual information or require a domain-specific action

5.3.2.2.1 Multiple object tracking task

The Helix (SAP, Walldorf, Germany) is a multiple object tracking assessment. The player stands facing a 180o curved screen (7 m width x 2.16 m height) and must track four out of eight simulated football players presented. The simulated players run around a football field for eight seconds in a randomized fashion and return to back to the start line up. Players must then identify the four players they were required to track. Players had four practice trials, and ten marked trials. The maximum score is 40 points, and is presented as a percentage, where 100% represents 40/40. There was no time pressure to provide a response. There was no time pressure to provide a response. The concept of multiple object tracking has been thoroughly investigated, with Faubert and Sidebottom (2012) highlighting the use of object tracking in sport.

5.3.2.2.2 Football-specific skills assessment task

The Footbonaut (CGoal GmbH, Berlin, Germany) is an innovative football-specific assessment tool that is designed to replicate the demands of a game in a standardized manner. The Footbonaut measure athletes' physical skills such as the first touch, dribbling and passing the ball, and their perceptual-cognitive skills as players are required to respond to visual and auditory stimuli. Players are assessed on a 14 x 14 m artificial turf surface surrounded by four walls. Together these walls consist of 64 target gates and 8 ball dispenser gates each 1.5 x 1.5 m, with two horizontal rows of gates per wall. Each gate is equipped with light barriers around the parameter and light-emitting diodes to measure the ball exiting and entering gates. During the assessment, a ball was dispensed from one of the eight possible dispenser gates at a speed of 50 km/hr. Immediately before the dispense of the ball, the lights along the perimeter of the gate light up and an audio signal was given to the participant to alert to the participant the location of the dispenser. This is followed by the same stimuli 0.8 seconds later from the location of the target gate, to which the participant is required to pass the ball into. Each participant had one practice round of 10 balls followed by two standardized sessions of 32 trials with a break in between. The mean reaction time (s) and accuracy (% correct) are recorded objectively by sensors.

5.3.3 Statistical analysis

The main objective in the current study was to investigate the changes in EFs over time. A latent variable modelling framework was used to describe how variability among observed outcomes from the different neuropsychological tests related to unobserved EFs. This is referred to in the model as latent variables (Dunson, 2000; Proust, Jacqmin-Gadda, Taylor, Ganiayre, & Commenges, 2006).

Figure 6 displays the conceptual framework of the latent variable model used in the analysis. The latent variable model comprised of two components: the structural model and the measurement model. Since the assessments conducted are classified as presenting or requiring either domain-generic or domain-specific information or action, two latent variables were introduced to include this distinction. The latent variables were modelled as a function of age in the structural model to describe changes in EFs as the players grew older. Observed outcomes were then linked to the latent variables through the measurement model. After accounting for the difference in performance that was due to age effects, individual outcomes were allowed to be directly affected by pre- or in-season testing session and playing position.

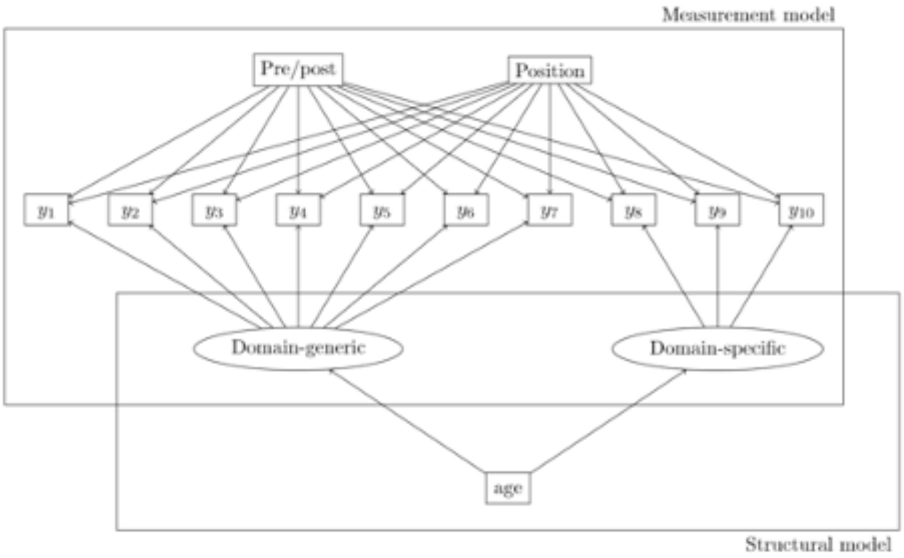


Figure 6: Path diagram of the latent variable model where the unobserved domain-generic and domain-specific executive functions were modelled as a function of age and were related to the measurements collected (variables y; see Supplemental Digital Content Table for the definition) through the measurement model. The measurement model also contained possible covariates (pre- or post-testing session and playing position) that directly affected the measurement variables.

Exploratory analysis as well as scientific considerations suggested that the age effects were likely to be non-linear (Crone et al., 2017; Zelazo et al., 2004). To accommodate this, a piecewise linear random effects regression model, also known as the "broken stick model" was used to allow for non-linearity in the trend. In this model, the general trend of the players' EF curves collectively followed the shape of a global trajectory representing the overall population. As players may exhibit heterogeneity in growth rates in each period of the four developmental stages, this variation was modelled using random effects which were assumed to be distributed according to a Gaussian distribution. By doing so, the slopes of each curve were allowed to deviate from those of the overall population, and thus each player had his own unique EF curves.

From a practical perspective, discrete variables relating to performance accuracy were transformed to continuous variables using the Gaussian kernel following Gelman et al. (2013). Variables related to the time taken to complete task were log transformed. Bayesian inference was performed (Gelman et al., 2013) for the latent variable model using Markov chain Monte Carlo sampling algorithm (Robert & Casella, 2004). The sampling of model parameters from their posterior distributions were implemented using the MATLAB (version 9.3) statistical computing environment. Estimated model parameters reported below in the results section corresponding to posterior means and highest posterior density regions were provided instead of confidence intervals.

5.4 Results

An exploratory data analysis of the longitudinal data was conducted to discover patterns of systematic variation. The example of log response time measurement from the Footbonaut test is used to illustrate this further in Figure 7, which shows the changes in mean log response time over the testing sessions for each playing position. The figure suggests that goalkeepers' performance was different from that of players in other field positions in the early periods of testing (i.e. 2016/17 pre-season testing to 2017/18 pre-season testing), where their mean response time improved consistently. Furthermore, the goalkeepers took longer to pass the ball from the dispenser gate to the target gate in the Footbonaut test. When comparing the performance within the same season, we found that all players did better during in-season testing, with possible exception of the defender group in the 2016/17 season. Overall, there was a general tendency for players' response times to decrease over the time between pre- and in-season testing. However, it must be noted that this improvement was confounded by the age of the players since they grew older between testing sessions. In order to investigate the age effects on cognitive performance, Figure 8 was plotted to show the relationship between log response time and age. The negative trend shown in all the plots suggested that the improvement in performance over time seen in Figure 7 was largely attributed to the age effects. It was obvious that the age effects were more significant in players below the age of 15, thereby necessitating a piecewise linear structure to model the non-linear age-related changes in EFs. The age effects were also responsible for the drastic drop in response time in the 2017/18 season compared to the previous season as there were more older players and no players below the age of 12 in the in-season testing session.

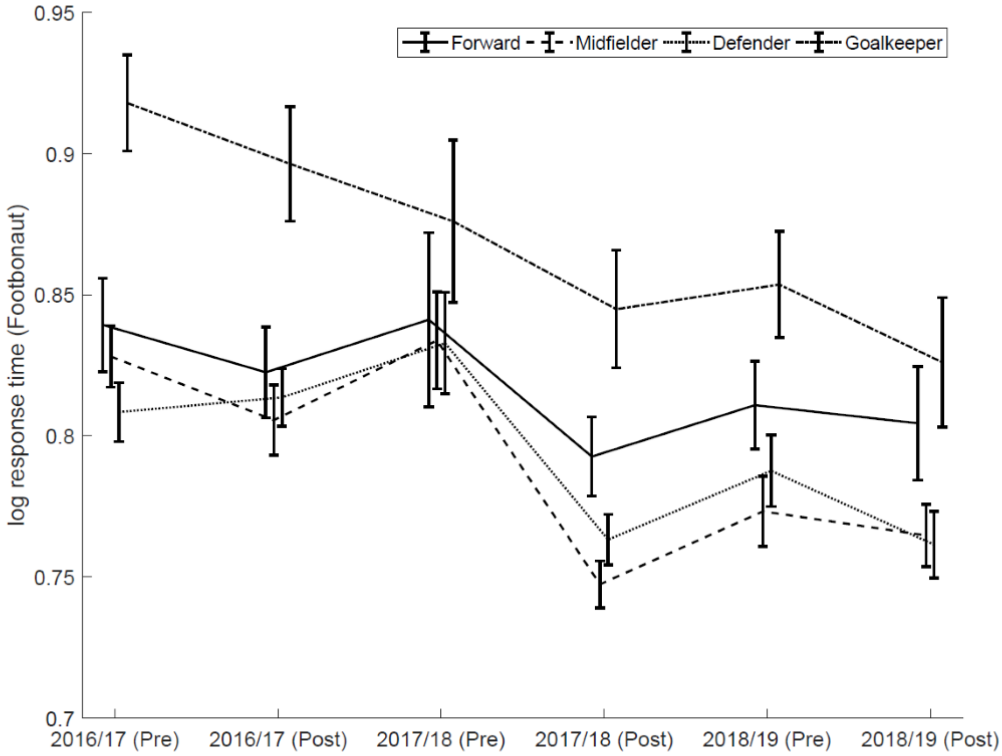


Figure 7: Changes in mean log response time from the Footbonaut test over the testing sessions for different playing positions. Error bars represent two standard errors of the mean.

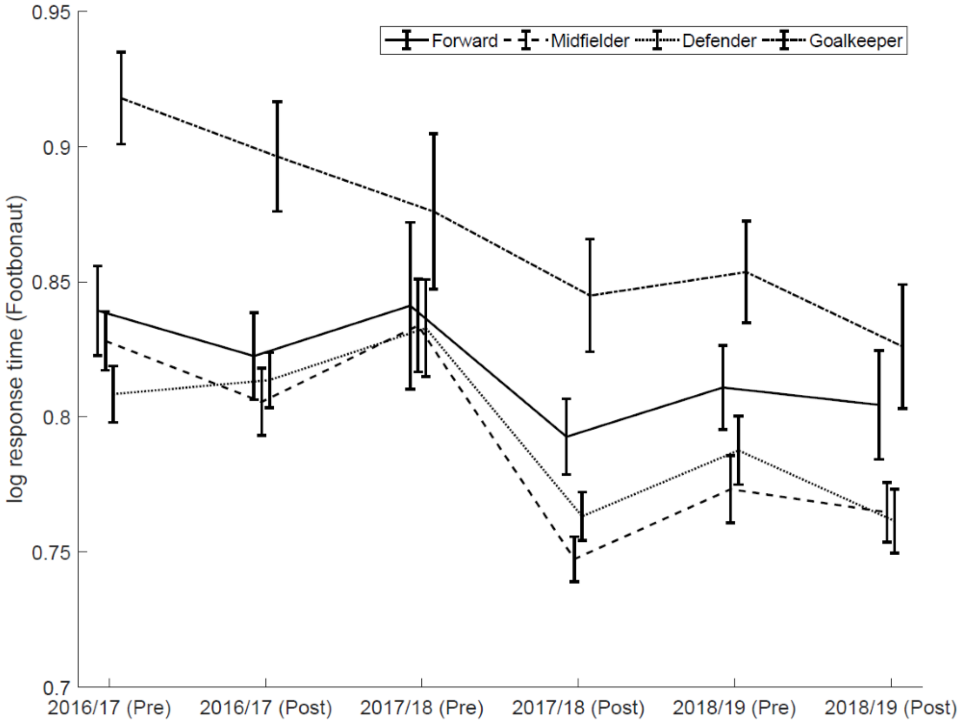


Figure 8: Relationship between log response time from the Footbonaut test and age in each testing session.

Following this preliminary investigation into the structure of the dataset, the latent variable model as described in the statistical analysis section was fitted, where the number of correct answers in the Determination test and the Helix test were chosen as the baseline scale for domain-generic and domain-specific abilities respectively. Table 7 shows the posterior mean estimates of random slopes in the broken stick model for each developmental stage of domain-generic and domain-specific abilities, while Figure 9 illustrates the resulting curves of the overall population graphically. It is evident that both facets of executive functioning demonstrated very similar trajectory patterns, whereby most of the development occurred between 10 and 15 years of age. While domain-generic abilities increased most rapidly (30 arbitrary units*year-1) during late childhood, domain-specific abilities showed the steepest increase (1.1 arbitrary units*year-1) during pre-adolescence. The average rate of development for both abilities then slowed down significantly (but still remained at positive values) when the players entered adolescence before accelerating slightly during early adulthood. This trend suggests that both general and specific cognitive abilities of football players reached adult performance levels during pre-adolescence.

Table 7: Posterior mean of random slopes for each developmental stage of domain-generic and domain-specific executive functions and their 90% highest posterior density (HPD) credible intervals.

	Developmental stages			
Abilities	Late childhood (10 – 12 years old)	Pre-adolescence (12 – 15 years old)	Adolescence (15 – 18 years old)	Early adulthood (18 – 21 years old)
Domain-Generic (au)	29.87	24.78	6.45	8.61
	(22.90, 37.42)	(21.28, 28.05)	(2.88, 9.90)	(5.07, 12.10)
Domain-Specific (au)	0.50	1.06	0.09	0.13
	(0.15, 0.89)	(0.85, 1.27)	(-0.03, 0.22)	(-0.04, 0.30)

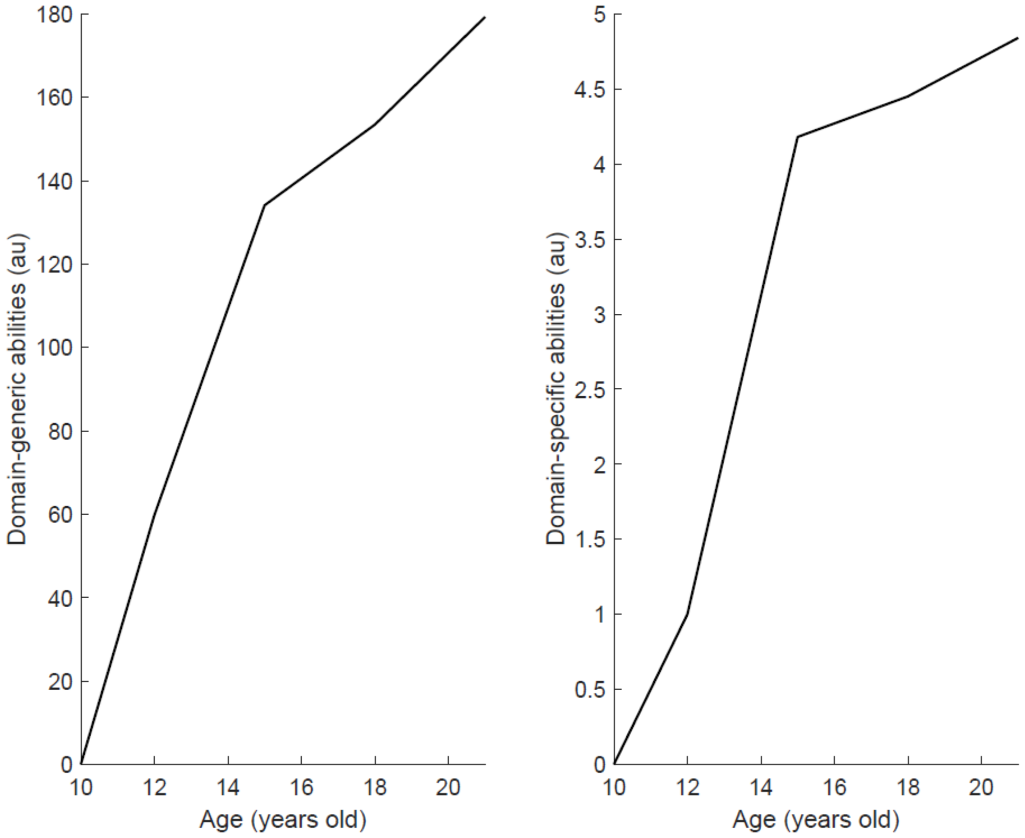


Figure 9: Posterior mean trajectories of domain-generic and domain-specific executive functions.

Finally, Table 8 shows the effects of covariates on the players' performance in each measurement variable. The results obtained indicate that the speed performance of players was better in the in-season testing sessions for all tests, even after accounting for the age effects. The average improvement varied between 0.65% (Footbonaut) and 8.65% (SSRT stop signal reaction time). It was also found that playing position only influenced the response time of players in the Footbonaut test. Goalkeepers had the slowest response time, and this corroborated with the findings in our preliminary analysis in Figure 7. Field players were shown to react faster by 4.35% (defenders) to 5.44% (midfielders) on average compared to the goalkeepers.

Table 8: Posterior mean of covariates for each measurement variable. Variables whose 90% HPD credible intervals do not include 0 are shaded.

Variable	Intercept	In-Season	Forward	Midfielder	Defender
y_1	138.8599	1.3346	0.0003	-0.0044	-0.0109
y_2	0.0135	-0.0270	-0.0011	0.0002	-0.0006
y_3	-1.2469	-0.0905	0.0035	-0.0389	0.0007
y_4	-0.6325	-0.0175	0.0042	-0.0026	-0.0014
y_5	81.8073	-0.2171	0.0650	0.0155	-0.3481
y_6	-0.4932	-0.0302	0.0007	0.0013	0.0020
y_7	-0.4372	-0.0372	-0.0001	0.0013	-0.0005
y_8	28.1646	0.0080	-0.0208	0.0154	-0.0009
y_9	22.9182	0.1424	-0.6141	0.2243	0.2563
y_{10}	1.0265	-0.0065	-0.0462	-0.0559	-0.0445

5.5 Discussion

The current study results challenge the previously reported relationship between EFs and football performance given the similar developmental trajectories that can be found in football players exposed to high-level football training and those found in the general population. Outcomes were modelled from a series of assessments of higher-level cognitive functioning that were performed by high-level football players across three years. Using a Bayesian approach to Structural Equation modelling, the effect of age on two latent constructs of domain-generic and domain-specific assessments was investigated. EF assessments were either considered domain-generic or domain-specific based on how either the perceptual information provided (i.e. the use of simulated players in the Helix assessment) or the sport-specific nature of the action required (i.e. passing towards targets in the Footbonaut) reflected those observed during football competition. While arbitrary, this subdivision reflects the general understanding of practitioners who use these assessments with a football milieu. The latent variable model used in this study examined the development of EF throughout four different developmental stages and demonstrated that domain-generic abilities developed at the fastest rate between late childhood into adolescence (10-15 years old), whereas domain-specific abilities underwent a more rapid growth during the pre-adolescence phase (12-15 years old). These observed rapid developmental increases in both abilities can be expected as previous longitudinal studies have also observed rapid increases in cognitive abilities during late childhood into pre-adolescence stages (Engelhardt et al., 2019). However, it is during the later stages of growth from adolescence into early adulthood where the findings of the current study reveal somewhat unexpected findings.

Previous research in general populations has demonstrated that domain-generic abilities increase rapidly between late childhood until reaching adolescence (Huizinga & Smidts, 2010; Zelazo & Carlson, 2012), and various measures of EFs can show continuous improvements into early adulthood (Huizinga et al., 2006). Aligned with the first hypothesis, these trajectories are also observed in the current study within high-level athletes, with large improvements apparent between the ages of 10-15 and steady yet considerably smaller performance improvements observed throughout adolescence and into early adulthood. The developmental trajectories of domain-specific abilities demonstrate similar growth curves, where rapid increases in performance are apparent prior to reaching adolescence. In some contrast, it appears that the onset of this growth is delayed slightly, with more observable increases occurring throughout the pre-adolescent period than during late childhood. Interestingly, an observable plateau of domain-specific abilities exists when players reach adolescence, with only slight increases into early adulthood.

The observed plateau for domain-specific abilities during the adolescent period contradicts previous research, and as a result opposes the second hypothesis of the current study. As both the environment and years of accumulated experience within an occupation are large contributors to improvements in domain-specific abilities (Li et al., 2004), it was expected to be reflected by steady improvements across all developmental stages leading into adulthood. Sporting environments are continuously challenging the cognitive abilities of each athlete, whereby players who persist in high-level performance settings such as high-level youth academies, are also those who have refined their perception-action coupling abilities to stay competitive (Mann et al., 2007).

A possible explanation for the plateau after the pre-adolescent period for domain-specific abilities is the choice of the assessments used in this study. The assessments administered may not have been sufficiently representative to truly assess domain-specific skills. The latent constructs of domain-generic and domain-specific assessments used in this study were based on an general understanding that the more an assessment looks like it is related to performance (i.e. the more football-relevant the perceptual information or the more football-specific the required action), the more specific the assessment is supposed to be of the demands of actual football (i.e. having high face-validity opposed to construct validity). Despite the attempts to utilize the best available tools to measure the athletes on assessments that are assumed to be highly realistic to football, both assessments are also limited in how they represent the perception-action couplings experienced by players during actual game-play (Pinder et al., 2011). For example, the Footbonaut yields a high action component but not a highly specific perceptual component to football (Beavan et al., 2018), and the Helix yields a high perceptual component specific to football but lacks an action component. Hence, the specific perceptual information may not have been adequately coupled with a sports specific action in either assessment (Pinder et al., 2011) and therefore may explain why the expected trends of a true domain-specific assessment were not observed.

The models in the current study also indicated that significant covariates exist that influenced the performance of players for different assessment variables. When comparing the second testing session with the first in the same season, athletes had better response times across all assessments, but the number of correct answers across each assessment did not improve. This may be attributed to athletes maturing over the months in between the sessions (i.e. roughly six months later) but could also indicate an acute habituation to ‘getting into the rhythm of training’ associated with assessing during the season rather than at the start. The other covariate included in the statistical models used in this study was playing position, where effects of playing position were only observed for Footbonaut response time. Goalkeepers, compared to other field positions, possessed slower response times. While this finding in part reflects the specific nature of the Footbonaut (passing and receiving passes related to visual and auditory stimuli), it is common for players - other than goalkeepers – to experiment with all other playing positions throughout their careers. Nonetheless, the absence of positional differences in the other assessments used in this study further highlights the lack of practical validity in using EFs as a prognostic tool for football talent. For example, Scharfen and Memmert (2019) proposed that cognitive testing could be used to help scout for talent, and even further suggested that position specific cognitive profiles could be created. Contrastingly, the current study's results firmly suggest that the association between EFs and sporting performance (measured through a longitudinal exposure to high-level football practice) is limited. Seemingly, a high degree of caution should be used when considering applying cognitive scouting or further implementing position specific cognitive profiling within a talent assessment battery.

Despite the relatively large sample size and comprehensive measures used in this study, there are a few notable limitations. First, the covariates within the sport itself were assessed such as the time of measurement and different playing positions on performance. However, the study did not control for other covariates that may influence the variability in EFs, such as IQ (Friedman et al., 2006), socio-economic status, biological or psychological maturity (Malina, Bouchard, & Bar-Or, 2004) number of languages spoken (Bialystok, Craik, & Luk, 2012), or external activities such as playing board games or playing musical instruments (Okada & Slevc, 2018). Future research should aim to incorporate the many possible external influences on EFs to understand their mediating or confounding relationships with athletes' EFs. Second, many athletes throughout their development experiment playing various field positions, which may account for the lack of observable playing position differences between all positions excluding the goalkeeper. Lastly, the validity of the reactive stress tolerance task and the stop signal task have previously been confirmed in populations above 15 and 16 years old respectively (Schuhfried, 2001), but not in populations below these ages. This should be taken into consideration for the results of the late childhood cohort. However, both these assessments have been used to measure the cognitive abilities of a large cohort (n = 600) of elite soccer players ranging from 11-19 years old, and all assessments used in the current study (including the Helix and PCRTT) have previously been used to measure high-performing soccer players from 10-35 years old (Beavan et al., 2020).

Practitioners are advised to exercise their due diligence to ensure that the 'football-specific' tools used to identify if a football player is talented, truly yields the capability to assess football specific skills. Various evaluations regarding the validity of each assessment are required to support their use in practice (Dicks et al., 2009), especially if a large emphasis is placed on their results. Finally, one form of validity that the current body of evidence is not able to answer is the predictive validity of domain-generic assessments, such as EFs, to know if a youth player with higher EFs will in turn have an advantage towards becoming a future adult professional. However, the current study's results exhibit that a high degree of caution should be had if using EFs within a talent identification battery, and practitioners should not over-emphasize the importance of such measures until further research is conducted.

5.6 Conclusion

In sum, researchers and practitioners must be cautious in attributing any sport-specific improvements to EFs in isolation, as an almost parallel development of more sport-specific cognitive abilities also exists that may be an underlying mechanism for sporting improvements. Therefore, despite their widespread use in practice coupled with previous cross-sectional studies inferring a relationship between EFs and football performance, the inclusion of EFs in talent identification batteries in youth football is likely questionable given the similar developmental trajectories that can be found in football players exposed to high-level football training and competition and those found in the general population. External research also suggests that specific types of pre-existing differences may influence EF development. Future researcher is required to better understand what other factors accentuate who does and does not pursue high-level performance attainment and how these additional characteristics predict who is likely to excel in sporting performances.

5.7 Supplementary tables

Supplementary Table 3. Number of observations per player, percentage of missing observations and the range of values in each measurement collected from the assessment battery. Note: The PCRTT and Helix were only used in two of the three seasons, and therefore have four possible testing sessions. This table shows the measurement variables, where the tests conducted were distinguished between assessments that presented domain-generic or domain-specific information. In general, the measurements were related to the accuracy and speed performance of the players. Due to the natural changeability of players within an academy, individuals participated in different number of testing sessions. Additionally, the PCRTT test and the Helix test were only included in the assessment battery in two of the three testing seasons. This led to a smaller number of observations per player, as well as an increase in the percentage of missing observations in both tests.

Assessment	Variable	Measurement	Number of observations per player	Percentage of missing observations	Minimum value	Maximum value
Domain-Generic						
Determination Test	y_1	Number of correct answers	0 – 6	2.79%	115	418
	y_2	Log response time	0 – 6	2.79%	-0.755	0.095
SSRT	y_3	Log stop signal reaction time	0 – 6	2.79%	-3.912	-0.677
	y_4	Log response time	0 – 6	6.65%	-1.221	-0.284
	y_5	Number of correct answers (out of 100)	0 – 6	2.89%	53	100
PCRTT	y_6	Log congruent response time	0 – 4	47.70%	-0.984	-0.293
	y_7	Log incongruent response time	0 – 4	47.70%	-0.860	-0.238
Domain-Specific						
Helix	y_8	Number of correct answers (out of 40)	0 – 4	43.73%	21	39
Footbonaut	y_9	Number of correct answers (out of 32)	0 – 6	22.08%	17	32
	y_{10}	Log response time	0 – 6	22.08%	0.604	1.191

Supplementary Table 4. We also examined the distribution of players according to the developmental stage of executive functions that they were in at the time of testing. Supplementary Table 4 showed that most players were between 12 and 18 years old when they participated in the test battery, whereas the late childhood category (between 10 and 12 years old) had the fewest number of players in all occasions.

	Developmental stages			
Testing session	**Late childhood (10 – 12 years old)**	**Pre-adolescence (12 – 15 years old)**	**Adolescence (15 – 18 years old)**	**Early adulthood (18 – 21 years old)**
2016/17 pre-season	20	60	61	32
2016/17 in-season	9	64	51	20
2017/18 pre-season	19	61	54	30
2017/18 in -season	0	59	54	29
2018/19 pre-season	19	56	47	31
2018/19 in -season	15	55	58	29

Chapter 6: A) Using Stroboscopic Vision to Restrict Visual Feedback in a Football Specific Skill Assessment

The content has been reformatted for the purposes of this thesis. The full reference details of the unpublished manuscript are:

Beavan, A., Fransen, J., Hanke., L., Spielmann, J., Skorski, S., Mayer, J., & Meyer, T. (In preparation). Using Stroboscopic Vision to Restrict Visual Feedback in a Football Specific Skill Assessment.

6.1 Abstract

Introduction: This study aimed to investigate how restricted visual feedback affects performance in a football-specific skill assessment that incorporates the coupling of perceptual information with motor actions. **Methods:** The Footbonaut is a 14x14 m cage equipped with 8 ball dispensers and 64 targets measuring passing accuracy, time to complete each pass, and a computer-generated point score for overall performance. Eighty-five amateur male participants (19.5 ± 5.4 years old; 13.1 ± 6.0 years football experience) completed two sessions under two different visual conditions: stroboscopic and full vision. Players were subdivided into skilled (S; top 50%) and less-skilled (LS; bottom 50%) groups using their point score from the full vision condition. According to the Specificity of Practice Hypothesis, it was hypothesised that greater performance decrements would be observed in the S group when visual information was restricted. **Results:** Results indicated that restricting visual feedback impacted time in both S and LS groups equally (S: 0.21s; LS: 0.18s; p=0.543), but S athletes' accuracy (S: 11.7%; LS:

0.4%; p<0.001) and point scores (S: 13653au; LS: 5391au; p<0.001) were significantly more affected compared to full vision conditions. **Conclusion:** Therefore, stroboscopic vision may be used to induce performance errors during practice to stimulate larger training effects, particularly in more skilled players.

Keywords: Attention; Vision; Motor Learning; Sports; Perception

6.2 Introduction

Vision is a fundamental source of afferent feedback during the execution of gross motor skills (Winnick, 1985). When motor skills become more complex and the surrounding environment becomes more dynamic (i.e. changes in information flow that occur during the execution of a motor skill), optimal use of visual information increases (Houwen et al., 2007). Movements carried out in fast-paced activities such as team-sports supports this statement. The high demand on visual processing for rapid and accurate information within a competition is essential, as athletes depend on a constant stream of updated information sourced from the complex and ever-changing environment (Davids, Williams, & Williams, 2005).

It is also common in sports for an object of interest to disappear temporarily from the field of view. For example, a football goalkeeper may lose sight of an oncoming ball temporarily during a free kick due to the defensive wall obstructing their vision (Ballester, Huertas, Uji, & Bennett, 2017). Moreover, a player dribbling the ball may momentarily lose sight of the ball whilst focusing on environmental information such as teammates or opponents (Fransen et al., 2017). Accordingly, a multitude of research protocols have been used to investigate how limited afferent information influences sporting performance (Mann et al., 2007). In several studies, limiting visual afferent information through the use of various forms of occlusion resulted in a decrease in performance of motor skills compared to when participants had normal vision. These effects have been demonstrated in both simple (i.e. a basic movement that requires a small cognitive involvement; such as a dart throw) (Proteau & Marteniuk, 1993) and more complex skills (i.e. a complex number of movements closely linked together, requiring a larger cognitive involvement; such as a football kick) (Fransen et al., 2017; Tijtgat, Bennett, Savelsbergh, De Clercq, & Lenoir, 2010; Ward, Williams, & Bennett, 2002).

Several studies have further investigated the importance of vision with respects to learning a motor skill, arguing that the enhanced ability to integrate sensory information with actions is vital for preserving and improving performance levels (Proteau, Marteniuk, & Lévesque, 1992). In these studies, participants appear to become more dependent on the feedback available to them as training progressed. This phenomenon is known as the Specificity of Practice Hypothesis (Proteau, Marteniuk, Girouard, & Dugas, 1987; Proteau et al., 1992). Collectively, these studies contradict the alternative concept, which states that the execution of closed motor skills becomes less dependent on afferent information with an increase in practice (Schmidt, 1975).

Many of the aforementioned studies have investigated the dependency of visual feedback when performing simple discrete movements (i.e. a motor skill has a well-defined beginning and end) in controlled laboratory settings. Hence, they provide limited external validity in sport. Recently, Fransen et al. (2017) reported similar findings of the negative impact that visual restriction has on the performance of a continuous football-specific dribbling skill. In a large sample of highly trained youth football players, dribbling performance across all ability levels (i.e. fast, average and slow dribblers) was significantly reduced due to the decrease in visual feedback. More specifically, participants with the fastest dribbling times in the control condition exhibited greater decrements in dribbling performance compared to participants with the slowest dribbling times when vision was restricted. Therefore, Fransen and colleagues (2017) provided support for the Specificity of Practice Hypothesis within a more complex motor skill more representative of football performance. However, football is an open-skill sport where external stimuli dictate the formulation and execution of a skill. Dribbling a ball around pre-set cones is a closed skill (i.e. predictable and self-paced) and may not be representative of dribbling during a game, which is an open skill. Thus, it remains unknown how restricted visual feedback affects other aspects of football-specific skill performance, particularly in tasks that encompass a perception-action coupling that is more representative of football game play.

Therefore, this study aims to investigate how restricted visual feedback impacts the performance on a football-specific skill assessment that requires a more complex and reactive perception-action coupling. According to the Specificity of Practice Hypothesis, it is hypothesised that performance decrements will be larger in more skilled participants compared to less-skilled participants when visual information is restricted.

6.3 Materials and methods

6.3.1 Participants

Eighty-five amateur football players were recruited from four clubs in Germany (n = 19 from the 6th division; n = 10 from the 7th division; n = 56 in 8th division). Participants were 19.5 ± 5.4 years old and had an average of 13.1 ± 6.0 years of experience playing football. One participant from the 7th division was removed from the data prior to the analysis due to equipment malfunction, resulting in a final sample of 84 players. Written informed consent was received prior to the commencement of the study from all participants or their legal guardian if participants were under the age of 18. Ethical approval was obtained by the ethics committee of Saarland University's Faculty of Empirical Humanities and Economics.

6.3.2 Footbonaut

Football passing performance was assessed using the Footbonaut (Christian Güttler, Berlin, Germany). The Footbonaut consists of a 14 x 14 m artificial turf surface and is surrounded by four walls. Together, the four walls consist of 72 square panels (64 target gates, 8 ball dispenser gates, each 1.5 x 1.5 m, divided into two horizontal rows). Each gate is equipped with light barriers around the perimeter, and light-emitting diodes (LEDs) measure the ball entering and exiting each gate. See Figure 10 for a schematic drawing of the Footbonaut.

6.3.3 Stroboscopic glasses

To limit visual feedback during the Strobe condition, participants wore stroboscopic glasses (Visionup, Kyoto, Japan) with LCD lenses that cycled between "open" (i.e. visual feedback) and "closed" (i.e. no visual feedback) states (frequency of 1 Hz, clear vision for 266ms, opaque for 620ms) replicating the visual conditions from a previously used methodology as closely as possible (Fransen et al., 2017). The glasses presented the individual with intermittent periods of occlusion that interrupt the constant flow of afferent visual feedback; forcing participants to link together disconnected temporal views of their environment (Smith & Mitroff, 2012).

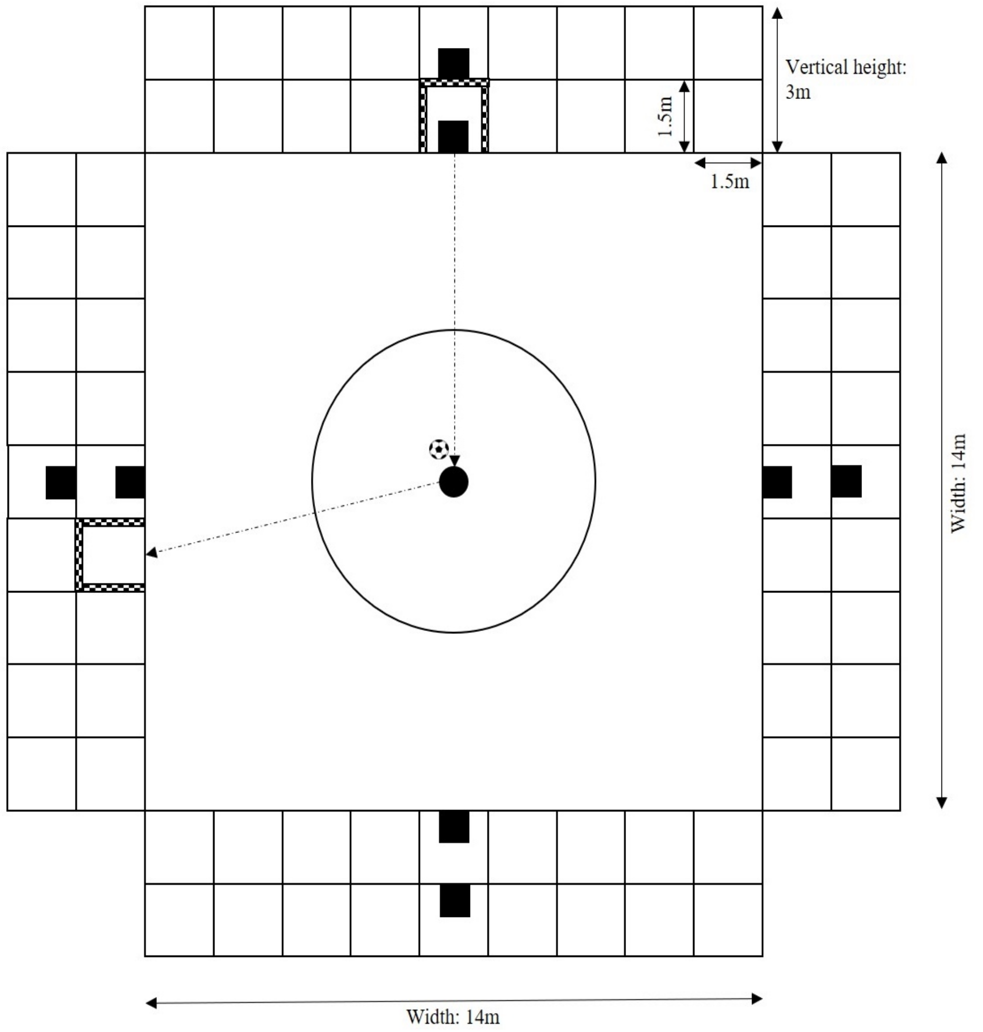


Figure 10. A schematic drawing of the Footbonaut, sourced from Chapter 3.

6.3.4 Procedure

Players were told not to perform any exercise the morning of the test. Prior to the commencement of experimental testing, each participant was provided with a demonstration of the stroboscopic glasses and of how the Footbonaut operated. Players received the instruction to "perform the assessment as fast and accurate as possible".

Following a familiarization of 10 trials, participants performed two assessment conditions consisting of a standardised combination of 32 consecutive trials with standardized parameters (see Table 9) separated by 10 minutes of rest. Players performed one assessment under a normal vision condition (Full vision) and a stroboscopic vision condition (Strobe) in a randomised counterbalanced order. A countdown of four seconds preceded the commencement of the test. Within each trial, an auditory and visual cue informed the participant which specific gate the ball would be dispensed from, and a second auditory and visual cue immediately identified the location of the target gate the player had to pass the ball into. The visual cue for the ball dispenser gate was a red light illuminated along its perimeter. The visual cue for the target was a green light illuminated around the perimeter of the specific gate. If the player did not pass the ball into the target after two seconds of the ball being dispensed, the target light would change colour to blue. After five seconds the light would change colour to white, and the trial outcome was considered to have resulted in "no goal". After the ball entered through a gate, the player had to swiftly return to the centre zone before receiving the next ball. No verbal encouragement during the session was given, nor were players told how many trials remained at any point.

Table 9. Settings defined for each condition in the Footbonaut.

Parameter	**Value**	**Description**
Balls	32	Number of balls dispensed
Ball Dispenser Power	50 km/hr	Speed of the ball
Vertical Angle	2°	Angle of inclination of ball-dispenser
Shot Delay	800 ms	Delay between when the auditory cue and the ball dispensed
Gates Used	360°	360°/360° gates used
Variables	**Value**	**Description**
Accuracy	Percentage (%)	Correct number of passes through the gates
Speed	Seconds (s)	Time the ball is dispensed until it enters the gate
Points	Arbitrary Unit (Au)	An algorithm comprised of accuracy, speed and location of gates in reference to the ball dispense

Note: Only the bottom row of gates was used during testing.

Time and accuracy variables were measured by the Footbonaut's LEDs. Time was defined as the time the ball is dispensed until it enters the target gate and measured to the nearest millisecond. Accuracy was defined as the number of correct passes through the gates in each session (out of 32). Lastly, an arbitrary point score was automatically generated by the Footbonaut's computer-based algorithm, and further investigation into the reliability and validity of the Footbonaut can be found in Chapter 4.

6.4 Statistical analysis

Players were subdivided equally into skilled (n = 42; top 50% of players) and less-skilled (n = 42; bottom 50% of players) groups using their point score from the full vision condition. First, an independent samples t-test was conducted to compare experience levels (i. e. years of training) between the two groups. Then a repeated measures multivariate analysis of variance (RM-MANOVA) with visual condition (full vision or stroboscopic vision) as a within-participant factor and skill group (skilled or less-skilled) as a between-participant factor was used to investigate the effect of restricted visual feedback on the Footbonaut performance of skilled or less-skilled players. Footbonaut points, accuracy and time were entered as dependent variables. Bonferroni corrections were used to investigate multiple comparisons between visual conditions and skill levels, and partial eta squared effect sizes were used throughout to investigate the magnitude of any observed effects using guidelines from Cohen (1988) to interpret effect sizes: 0.01-0.06 = small effect, 0.06-0.14 = moderate effect and >0.14 = large effect. Statistics were analysed using SPSS 24 (SPSS, Inc., Chicago, IL, USA). Criterion alpha level for significance was set at $p \leq 0.05$.

6.5 Results

No differences in playing experience between skilled and less-skilled groups were observed. A RM-MANOVA revealed a significant condition*skill group interaction effect on Footbonaut performance ($F(3,80) = 7.43$, $p < 0.001$, ES = 0.22), and significant skill group ($F(3,80) = 8.09$, $p < 0.001$, ES = 0.23) and visual condition ($F(3,80) = 38.26$, $p < 0.001$, ES = 0.59) main effects. Further univariate analysis identified that there is a significant condition*skill level interaction effect on accuracy (F(1,82) = 14.02, p < 0.001, ES = 0.15) and points (F(1,82) = 17.97, p < 0.001, ES = 0.18) but not on time (F(1,82) = 0.37, p = 0.543, ES = 0.01), where performance decrements in accuracy and points were greater in relatively skilled performers than less-skilled performers (Δaccuracy skilled: 11.5%, Δaccuracy less skilled = 0.5%; Δpoints skilled: 13653.0 points, Δpoints less skilled = 5390.9 points). In total, accuracy (F(1,82) = 16.50, p < 0.001, ES = 0.17) and points (F(1,82) = 95.49, p < 0.001, ES = 0.54) were significantly lower in the strobe condition (accuracy = 59.81 ± 16.53 %, points = 37637.3 ± 13109.7 points) than the full vision condition (accuracy = 65.90 ± 14.46 %, points = 47159.2 ± 14379.6 points), while time (F(1,82) = 68.79, p < 0.001, ES = 0.46) was significantly higher in the strobe condition (2.75 ± 0.29 s) than the full vision condition (2.55 ± 0.27 s). Descriptive statistics for performance in the Footbonaut with means ± SD, 95% confidence intervals, F values, P values and partial eta squared effect sizes are presented in Table 10.

6.6 Discussion

The aim of the current study was to examine the influence of restricted visual feedback on the performance of a dynamic football-specific task that incorporated a coupled perception of visual cues with the execution of a football-specific motor action. In support of the hypothesis, restricting visual feedback significantly affected the performance of football players in a football-specific skill assessment. Furthermore, skilled participants' accuracy and points were impaired to a greater extent when compared to less-skilled players. These findings extend the Specificity of Practice Hypothesis to a more dynamic and representative task in sport that heavily relies on the perceptual-cognitive processes to dictate the movements of the player.

Overall, both groups displayed poorer performances in the stroboscopic conditions in comparison to the full vision condition. The observed decrements in performance are comparable to research that has reported the impairment of motor skill performance when vision is manipulated in simple discrete tasks such as manual aiming (Proteau et al., 1987; Proteau et al., 1992) and more complex tasks such as a football-dribbling course (Fransen et al., 2017) or one-handed catching (Tijtgat et al., 2010).

Table 10: Descriptive statistics and between-condition, group, and interaction effects for accuracy, time, and points during performance on a football-specific skills assessment task with restricted visual feedback

	Less-skilled (n = 42)		Skilled (n = 42)		Condition		Skill group		Interaction	
	Full vision *Mean±SD* *(95 % CI)*	Strobe *Mean±SD* *(95 % CI)*	Full vision *Mean±SD* *(95 % CI)*	Strobe *Mean±SD* *(95 % CI)*	*F* value	ES	*F* value	ES	*F* value	ES
Accuracy (%)	59.38±15.05 (55.40-63.36)	58.90±17.78 (53.81-64.00)	72.43±10.45 (68.45-76.41)	60.71±15.35 (55.62-65.81)	16.498**	0.17	6.639*	0.08	14.021**	0.15
Time (s)	2.68±0.27 (2.60-2.75)	2.86±0.25 (2.78-2.94)	2.43±0.22 (2.35-2.50)	2.64±0.29 (2.56-2.72)	68.785**	0.46	21.723**	0.21	0.374	0.01
Points (Au)	39078.6±10959.3 (35415.5-42741.6)	33687.7±11187.1 (29829.5-37545.9)	55239.9±12833.7 (51576.9-58903.0)	41586.9±13109.7 (37728.7-45445.0)	95.487**	0.54	23.334**	0.22	17.973**	0.18

Note: * = p<0.05, ** = p<0.01; SD = standard deviation; CI = confidence interval, ES = partial eta squared effect size

The performances of the participants in the skilled group were significantly more negatively affected than those of the less-skilled group when vision was restricted. The results of the current study provide support for the Specificity of Practice Hypothesis, which states that greater performance decrements in motor skill performance are apparent in more experienced participants when afferent feedback conditions are dissimilar to the environment in which they learned the skill (Proteau & Marteniuk, 1993). Previous research has similarly confirmed the Specificity of Practice Hypothesis (Fransen et al., 2017; Ivens & Marteniuk, 1997; Proteau & Cournoyer, 1990; Proteau et al., 1992; Whiting, Savelsbergh, & Pijpers, 1995), reporting that movements become progressively more dependent on visual feedback with greater amounts of practice and with increased skill levels. Thus, as the participants in the current study had high levels of playing experience, the larger decrements of performance due to visual restriction were expected.

Although the observed decrements in sporting performance may be largely attributed to the Specificity of Practice hypothesis, there may be a second explanation for the results found in this study. Maintaining performance standards under restricted visual feedback conditions is effortful and attentionally demanding (Ballester et al., 2017). The unusual increase of attentional resources during the performance in the Footbonaut may be consequential to performers in a variety of ways. Firstly, in line with the results of the current study, Fransen et al. (2017) reported that players' speed was negatively affected when subjected to stroboscopic conditions. Fransen et al. (2017) further reported that the fastest dribblers also demonstrated the largest speed decrements when vision was restricted in comparison to the slower dribblers. The authors attributed this effect to a larger change of ball position between intermittent visual feedback with the speed of the movement, making occlusion more difficult for faster dribblers. Yet in the current study, both skill groups had equally slower performance decrements in the strobe condition compared with their full vision condition. Thus, it appears that both groups' time was affected by having to compensate for the changes in ball position during occluded periods.

Although the performance variable time was equally affected within both groups between full and restricted visual feedback conditions, skilled athletes had a significantly larger decrease in accuracy and points in comparison to the less-skilled group. One potential explanation may be that skilled players had to spend more attention towards the oncoming ball, regressing players back to a step-by-step process of independently tracking the ball prior to searching for the target location despite having superior visual tracking abilities (Uchida, Kudoh, Higuchi, Honda, & Kanosue, 2013). Previous research demonstrated that when in full vision conditions, highly experienced football players have the perceptual-motor coordination that allows them orientate their attention towards player-directed areas during the reception phase of the oncoming ball, and only attend to the ball when performing the first touch (Oppici, Panchuk, Serpiello, & Farrow, 2017). However, restricting visual feedback may change the allocation of attention. Similar to a person using their high-beam lights whilst driving to provide extra illumination when normal lights are insufficient, an object tracking study demonstrated that participants appear to provide a surplus of attentional resources when tracking an object to compensate under stroboscopic conditions; known as the "high-beam effect" (Flombaum, Scholl, & Pylyshyn, 2008). Therefore, the irregular distribution of attentional resources may in turn reduce the salient information in the environment necessary to process perceptual information (Wickens & McCarley, 2007). As a consequence, players may not be able to receive adequate target location information concurrently with the oncoming ball.

Moreover, a decrease in spatiotemporal information gathered from the target location may have affected the planning of movement kinematics in advance (Tijtgat et al., 2010). Consequently, the pressure of maintaining speed in turn may cause an inaccurate pass (Beilock, Bertenthal, Hoerger, & Carr, 2008). Contrastingly, the less-skilled players may not yet possess the ability to simultaneously search for the target whilst predicting the time to contact of the approaching ball. Therefore, the less-skilled players' pattern of receiving the ball and subsequently searching for a gate may have remained consistent between conditions, and therefore may explain their smaller decrements in accuracy between conditions. However, the current study did not use any equipment to measure perceptual ability such as eye-tracking (Vaeyens et al., 2007) or other estimations of spatial attention allocation (McGuckian & Pepping, 2016). Therefore, future studies should incorporate similar technology in an attempt to provide further insight into the disruption of movement planning in conjunction with limited afferent visual information.

Lastly, the possible increase in attentional demands during the execution of a task-specific skill may have regressed the player from a higher stage of learning a skill where movements are largely controlled automatically with little cognitive engagement, into a lower stage of learning characterised by more cognitive engagement (Fitts, 1964).

Numerous studies have demonstrated that an abnormal change in allocation of attention has negative effects on the performance of motor skills in sport (Beilock & Carr, 2001; Lohse, Sherwood, & Healy, 2010). Furthermore, conditions that direct attention to the unfolding of performance hurt skilled performers more than less-skilled performers (Beilock, Jellison, Rydell, McConnell, & Carr, 2006) further supporting the results of the current study.

Despite the current study extending fundamental concepts of motor control into a more representative sporting assessment task, the present experiment is not without limitations. First, the pre-determined frequencies of the glasses from a separate manufacture have not made it possible to exactly match the frequency from previous work (Fransen et al., 2017). In the current study, the vision was in an "open" state for 166ms longer, but frequency and "closed" state values remained similar. For example, the present study (frequency of 1 Hz, clear vision for 266ms, opaque for 620ms) differed from Fransen et al., (2017)'s study (frequency of 1.33 Hz, clear vision for 100ms, opaque for 650ms). Second, a limitation in all studies using stroboscopic glasses is that the "closed" state does not fully occlude. Therefore, players may have had an advantage to process more information during each second in comparison to previous studies, which may have lessened the impact of visual restriction in the Footbonaut.

In summary, skilled athletes demonstrated larger decrements in performance compared to lesser-skilled participants when subjected to restricted visual conditions. The study's findings are in support with the Specificity of Practice Hypothesis, and further propose that a change in the allocation of attention may cause more skilled athletes to change information processing, and consequently impacting their accuracy during the execution of a continuous motor skill. Thus, stroboscopic vision may be used to induce performance errors during practice to stimulate larger skill training effects, particularly in more skilled players.

6.7 Practical applications:

Practitioners can use glasses that restrict visual feedback to increase the skill demands of training and help induce performance errors during training on an individual basis, particularly in more skilled athletes (i. e. using various levels of visual restriction between players). These performance errors could in-turn induce larger skill training effects in targeted athletes without compromising the speed of execution of motor skills and ultimately the flow of the training drill.

Chapter 6: B) The Association between Visual Exploration and Passing Performance in High-Level U13 and U23 Football Players

The main author of this thesis assisted in another research group's research project that studied the effects of visual exploratory actions inside the Footbonaut. The following study attempts to understand the perceptual behaviours of athletes both prior to and during ball contact. A second major outcome of this study demonstrates the beneficial use of implementing this new age technology - being inertial measurement sensors mounted onto the head of athletes - in attempt to further understand the perception and action demands of football actions in the skills assessment task. The assessment task provides a 360-degree environment that allows athletes to orientate their head in a similar fashion to pick up environmental cues as in real match-play, having practical relevance for the Footbonaut's use. Possibly, the Footbonaut could provide a valuable platform to further promote researcher's understanding of how exploratory behaviours transfers from standardised training scenarios to more representative on-field settings. Notably, the study contained in Chapter 6(b) could not be published as part of the current thesis, however a summary of the study and the supporting literature is provided below. The full reference details of the unpublished manuscript are:

McGuckian, T., Beavan, A., Mayer, J., Chalkley, D., Pepping, GJ (In press). The association between visual exploration and passing performance in high-level U13 and U23 football players. *Science and Medicine in Football.*

6.8 Overview of literature

The Footbonaut is an assessment tool that evaluates the technical control, passing and shooting ability of football players in an unpredictable and 360-degree environment. This assessment tool is renowned for its highly technologically advanced system that allows athletes to be constantly engaged in an environment that was designed to be a realistic assessment task. However, despite the Footbonaut being able to discriminate between younger and older players (as depicted in Chapter 4), the main perceptual-motor contributors that underpin these differences in the Footbonaut remains unclear. Therefore, aligned with the theme of this chapter of introducing appropriate technologies to better understand perceptual-motor performance in the Footbonaut and improve the usability of the Footbonaut, there is a need to quantify the perceptual aspects that relate to improved passing performance.

Previous research has demonstrated that the perceptual-motor abilities of players are strongly linked with the performance of technical actions in sport (Dunton, O’Neill, & Coughlan, 2019; McGuckian, Cole, Jordet, Chalkley, & Pepping, 2018b). Recently, a new perceptual-motor factor has been given a large amount of attention. The visual exploratory action (VEA) that occur in the moments leading up to receiving the ball has consistently demonstrated a positive relationship with successful passing performance (Jordet, 2005; McGuckian, Cole, & Pepping, 2018c). These VEA can be described as the “turning of the head about the longitudinal axis that allows athletes to gain information about their surrounding environment” (McGuckian et al., 2018a). During a football match, athletes are constantly rotating their head (i.e. looking left and right) with various intensity (i.e. the difference between looking to what is in front of them vs. looking over their shoulder to see what is behind) in order to gain a large amount of environmental information. Such exploratory actions could help gain a better awareness of the positions of both teammates and opponents, searching for free space to move, and understanding where their position is on the field relative to the play, amongst many others (Jordet, Bloomfield, & Heijmerikx, 2013). These VEA are essential especially in a team-sport environment such as football, where the field of play is constantly changing around the athlete with a large amount of unpredictability.

Typically, researchers have focused on three main VEA (McGuckian et al., 2018a). First, head turn count (HTC) is the total number of head movements completed in a specific time frame. Second, head turn frequency (HTF) signifies the number of head movements per second. Together, HTC and HTF provide information related to *how often* a player is changing their visual orientation to perceive their environment (Chalkley, Shepherd, McGuckian, & Pepping, 2018). For example, in a laboratory-based test, football athletes had an average of 1.96(0.81) head turns (i.e. HTC) when only given one second to explore the environment prior to receiving the ball compared to 6.31(1.79) head turns when given three seconds to explore (McGuckian et al., 2018a). Furthermore, Jordet et al (2013) recorded that some of the best midfielders in football (i.e. Frank Lampard and Steven Gerrard an HTF of 0.62 and 0.61 respectively. In other words, Frank Lampard would make on average 6.2 head turns in the 10 seconds leading up to the moment he received the ball. Importantly, Jordet et al (2013) and McGuckian et al., 2018a) have different definitions for what constitutes a VEA, reducing the ability to directly compare the results between in-lab and on-field exploratory actions. Third, head turn excursion (HTE) represents the total size (in degrees) of head movements per second (Chalkley, Shepherd, McGuckian, & Pepping, 2018; McGuckian, Cole, Chalkley, Jordet, & Pepping, 2019; McGuckian et al., 2018b), providing information on *how much* of the environment a player is exploring (Chalkley et al., 2018; Freedman, 2008; McGuckian et al., 2018b). This allows the researcher to objectively determine how large the head turn was for the athlete, 0 degrees representing an athlete looking straight ahead in a neutral position, and larger angles representing a search to the side. Importantly, these VEA are also related to the time at which they were initiated. VEA before the player has possession of the ball may represent athletes prospectively searching for opportunities to play the ball, whereas VEA while in possession of the ball may represent a confirmation of target location but could also represent a search for opportunities in the environment if not sufficiently completed earlier.

It has been reported that athletes who display higher VEA prior to receiving the ball is linked with higher pass success (Jordet, Bloomfield, & Heijmerikx, 2013) and faster passing responses (McGuckian et al., 2019). Specifically, athletes who had >3 head turns/sec (i.e. HTF) before receiving the ball were -0.52 seconds faster on average compared to athletes who only turned their head between 0-1 head turns/sec to respond in a football specific decision-making test. However, a few notable limitations currently exist in this research area. First, Jordet et al. (2013) demonstrated the importance of VEA using game recordings of players in the English Premier League. However, film-based observations of VEA in an natural playing environment did not allow for any objective data, and therefore head movements were subjectively assessed. McGuckian et al. (2018a) expanded on this research by being the first to objectively measure head movements with clear criteria as to what constituted a true VEA using 9-DOF Inertial Measurement Unit (IMU; IMeasureU Blue Thunder, Vicon, Oxford, UK) at 500 Hz (Chalkley et al., 2018; McGuckian & Pepping, 2016). In a follow up laboratory-based setting that athletes were tested in, athletes were required to kick a sports cone that corresponded to the intended teammate who was displayed on a computer monitor. Although this study attempted to incorporate perception-action coupling, the relatively simple and restricted expression of movement were underrepresenting the natural actions that athletes are accustomed to. Therefore, the study by McGuckian, Beavan, Mayer, Chalkley, and Pepping (In press) aimed to address a gap in the current literature by investigating the association between VEA variables on passing performance in the Footbonaut, as this assessment task has a highly similar interaction between the actions required when receiving and passing the ball on a large turf surface as with on-field actions.

6.9 Overview of Study

In order to understand the differences between why the older athletes were faster than the younger athletes in Chapter 4, McGuckian et al. (In press) recruited both U13 and the U23 cohorts. The researchers hypothesised that older players would use more extensive VEA before receiving possession of the ball than younger players, and that more extensive VEA before receiving the ball would contribute to better performance on the football passing task. Aligned with the methodologies of previous research in analysing head movements of athletes (Chalkley et al., 2018; McGuckian et al., 2018a; McGuckian & Pepping, 2016), head movement data were collected with the aforementioned IMU devices by placing the sensors inside an elastic headband and worn by the athletes. The testing procedure consisted of a standardised combination of 32 trials as described in Chapter 4.

Aligned with the results of Chapter 4, the U23 group were faster on average across all trials in the Footbonaut. More interestingly, the results demonstrated that a higher head turn count before a player received the ball was associated with a reduced time to complete trials, whereas a higher head turn count after a player received the ball was associated with an increased time to complete trials (McGuckian et al., In press). These findings are in line with previous research on the positive relationship between VEA and response time (McGuckian et al., 2018a). Moreover, older players explored their surroundings more before gaining possession of the ball, and less after receiving the ball, whereas the younger group explored less before receiving the ball and more after receiving the ball. One further interesting finding was that midfield players were able to complete passes more quickly than other playing positions (McGuckian et al., In press), which may be attributed to the midfield role considered to be more observant in a 360-degree field of play during games than other positions. In sum, the results demonstrated that athletes are more proactively searching for opportunities to act on once receiving the ball, whereas younger athletes may be searching for these opportunities after receiving the ball, and hence delaying their response times.

Whilst the findings further our understanding of perceptual and passing performance in the Footbonaut, it is important that these results should be considered within the context of the limitations of the Footbonaut that have been highlighted throughout this dissertation, particularly in Chapter 5. The Footbonaut offers a strong experimental control setting, but the perceptual information that is perceived in order to act is dissimilar to the information that is normally available to a player during match-play (Dicks, Davids, & Button, 2009; Pinder, Davids, Renshaw, & Araújo, 2011; Travassos et al., 2013). It is not clear, to what extent this perceptual information changes the normal VEA of players, however, the findings still demonstrate clear positive effects of VEA on performance in football related actions in the Footbonaut. Furthermore, these results can be seen as a steppingstone for improving the ecological validity of the testing environments that VEA have been previously measured in. The logical next step would be for these results to be compared with on field environments to understand if they are reflective of VEA in match-play or not. Until then, caution should still remain when generalising these findings to more representative football training and match-play (McGuckian et al., In press). Together, it is recommended that future research investigates the similar and contrasting properties of numerous technical abilities (i.e. passing, shooting and dribbling) and perceptual abilities (i.e. VEA and visual search behaviours) between standardised assessment tasks and more representative training and match-play environments. Such research will also further promote our understanding of whether and how exploration behaviours transfer from standardised training scenarios to more representative on-field settings (McGuckian et al., In press).

Chapter 7: General Discussion

This chapter presents a general discussion of the thesis, which includes a summary of the findings across each study, limitations, practical guidelines for implementing assessment tasks, and recommendations for future research.

7.1 Summary of findings

7.1.1 Preliminary investigation on executive functions in high-level football players

The first study that was reported in this dissertation was a was a two-part probing investigation into the relationship between age and EFs in high-level football players; reported in Chapter 1 (and full manuscript found in the appendices section 8.1). The aim of this preliminary investigation was to set the groundwork for understanding if there was a rational basis for continuing using EFs based on previous evidence within the literature and our own preliminary attempts.

The first part of the probing investigation was to bring attention to the fact that all of the cognitive assessments used in the previous literature were providing only explicit (i.e. clear and obvious) information to the participants. However, these assessments do not consider or reflect how much of the information that humans perceive is largely implicit (i.e. not obvious or attended to), as it is impossible to consciously attend to everything that is happening in our environment (Kibele, 2006). Therefore, the integration of a new implicit EF assessment using the choice reaction time task paradigm was integrated into the EF battery and the justification of its methodology can be further explained by Barela et al. (2019). The newly developed task aimed to measure the impact that implicitly perceived visual information had on the response times of high-level athletes. The results from this specific assessment implied that athletes undergoing development throughout adolescence coupled with gaining more game-specific experience in rapid decision-making scenarios translates to a more refined ability to (i) use congruent precues to their advantage, and (ii) consistently negate unimportant information from incongruent precues than players with less experience. These findings could have important implications for sport coaching. For example, training a player's ability to consistently not act on irrelevant cues throughout the duration of the match has important implications for decision-making in sport. There is a myriad of examples in sport where unimportant information surrounds athletes. For example, players attempting to provide the opponent with false information to gain an advantage (i.e. a pass-fake in a team sport), or visual and auditory distractions from the crowd during a basketball free throw.

The second part of the investigation was to examine the age-related changes in more specific age groups. Previous methodologies that measured the EFs of football players have grouped players with large age ranges, such as ranging between 12-19 years old (Vestberg, Reinebo, Maurex, Ingvar and Petrovic 2017). However, according to research outside of a sporting domain, many studies report that executive functions are still rapidly developing during the adolescent periods prior to adulthood (Zelazo 2004, Li et al., 2004, Luna, 2009), and therefore should not be grouped together due to age being a strong covariate of EF development. Therefore, the second part of the study aimed to use four distinct age-specific groups to examine more distinct age group differences.

The results from this investigation found that older football athletes (U17-U19) performed better compared to their younger counterparts (U12-U13) on a series of cognitive functioning assessments that measured EFs. In summary, the preliminary study of the thesis found that older athletes with more experience playing football had better EFs than younger athletes. Furthermore, the magnitude of difference between the younger cohorts was larger than between the older cohorts, indicating a larger development of EFs during early adolescence compared to late adolescents. Therefore, this study set the foundations for additional studies that include more age specific cohorts in order to properly map out the true developmental curves from childhood into adulthood. Lastly, although this study demonstrated that older and more experience athletes outperformed their younger counterparts, it was not able to determine what the attributed factors were that contributed to these superior cognitive performances. Hence, this was the major aim of the subsequent study reported in Chapter 3.

7.1.2 Contributors to executive function development in a football-specific population

Chapter 3 aimed to overcome the many limitations of the literature and expand upon the foundations that the first initial investigation had built in Chapter 1 with an emphasis on investigating if athletes are born with their EF profile, or has it been nurtured through engaging in sport.

First, no previous study has investigated how EFs develop between specific age groups of athletes, let alone high-performing athletes. In order to 'fill in the gaps' from the preliminary study, more age-specific cohorts were required. A second limitation of the current research was stated in Scharfen and Memmert (2019)'s review, reporting a failure of the meta-analysis to confirm whether it is nature or nurture that is the main contributor to better cognitive functions observed in higher-level athletes in comparison to their lower-level counterparts (Voss et al., 2010). Therefore, Chapter 3 further aimed to examine whether chronological age (i.e. in support of the nature argument) or years of experience playing football and playing position (i.e. goalkeeper, defender, midfielder or forward; in support of the nurture argument) had larger influences on EF performance in a large homogenous population of high-level football players.

By analysing nine age groups from the U12 to the senior professional teams over three seasons, Chapter 3 documented the age-related changes in EFs that occurred throughout the entire phase of early childhood into adulthood in a high-level football-specific population. Collecting data for three seasons allowed for a high sample size (n = 343) and to become a mixed-longitudinal dataset due to the natural changeability of athletes coming in, staying and/or leaving the academy at various time points throughout the duration of data collection.

The results were in support of the nature argument, demonstrating that a player's age was a stronger contributor to their EF performance across the entire EF battery compared to their number of years of experience playing football or which playing position athletes were. Age itself only explained a low to moderate percentage of the variance (0 - 57%), yet this explained power was higher than that of experience (0 - 49%), whilst playing position did not appear to contribute noticeably to EF performance. Genetic research also provides evidence in support of the nature argument, indicating that EFs are almost entirely (99%) attributed to genetics with very little contribution (<1%) from environmental influences (Friedman et al., 2008).

The results from Chapter 3 did not support that environmental factors are large contributors to EF performance; players with higher levels of experience did not appear to possess higher EFs. It is more likely, that players with higher levels of experience are also the older aged athletes, and therefore display slightly better levels of EFs due to an increase biological development (Huizinga et al., 2006). Thus, the previous suggestions that playing sport improves EFs or EF abilities contributes towards differences in sporting expertise are demonstrations of how many previous claims in research of the potential future use of EFs in sport are unjustified. A further example of this overreach was proposed by Scharfen and Memmert (2019), stating that cognitive testing could be used to help scout for talent, and even further suggested that position specific cognitive profiles could be created to aid in talent identification programs. Contrastingly, Chapter 3 was the first study to investigate this claim in large cohort of high-level football athletes and firmly suggests that the association between EFs and athletes that are exposed to high-level football practice is limited. Seemingly, a high degree of caution should be used when considering applying cognitive scouting or further implementing position specific cognitive profiling within a talent assessment battery.

Another noteworthy observation in the data contained in Chapter 3, is that a large between player variation exists within each EF test. This represents that players in the same age-group cohort appear to possess vastly different levels of EFs, and this variation was consistent across each age group from the U12 to the professionals. This variation has also been observed in other studies examining athletic populations (Ishihara et al., 2018; Sakamoto et al., 2018). Such variation is to be expected, as there is also a large variation of EFs expression within the general population. Some individuals are able to regulate their own thoughts and actions, while others struggle to control their behaviour and are ruled by impulse (Friedman et al., 2008). However, if a high level of EFs were required, then one might assume that progressively throughout the older age groups of an academy, players who express high levels of EFs should in theory be kept in the academy, while the ones that could not keep up with the mental demands of the game were removed. This however was not apparent, as even some professional players displayed poor levels of EFs.

Interestingly, Chapter 3 also denotes that when the EF data was plotted with age, the developmental curves of the high-level athletes appeared to follow the theoretically predicted trends that are observed in general populations (Crone et al., 2017; Li et al., 2004; Zelazo et al., 2003). Specially, athletes in this sample reached their maximum level cognitive performance at comparable ages with the general population (mid 20's), further supporting that the developmental process of EFs is not accelerated by playing football. Another observation made on the developmental trends was that the athletes appeared to undergo the same cognitive decline as the general population. The plateau of athletes after they reached their maximum level of performance was followed by a slight decrease performance. The drop in EF performance indicates that engaging in high-level sport is not a strong enough stimulus to negate or even somewhat delay the onset of the natural decline of human's cognitive abilities.

Another interpretation of the observed cognitive decline from the adult (>21 years old) athletes contained in the sample is that these athletes are also the professional first team players within the collected sample. These senior athletes were competing not only in the highest club competitions in Europe during the time of data collection (i.e. champions league 2018), but roughly half of the squad were also a part of their respective national teams that also played at the World Cup in 2018. Interestingly, a separate survey on 185 players in the United Kingdom reported that these players signed a professional contract at the average age of 18.2 ± 2.4 (range: 16-27 y) with the average age of retirement was 32.5 ± 5.2 (17-42 y) (Drawer & Fuller, 2002). Thus, the general age range of a professional football player's career indicates that they are spending a large majority of their professional playing time in either a plateau phase of their natural cognitive abilities or in cognitive decline.

Albeit, in order to confirm whether the EFs developmental curves reflected that of the general population, a true longitudinal study was required to map out the developmental curves of EFs in athletic population, which has previously not been examined.

7.1.3 Suitability of executive functions within a football domain

Accordingly, one of the main aims of Chapter 5 was to document age-related changes in EFs in a longitudinal manner based on the prior assumptions about the data sourced from Chapter 3. Longitudinal studies in general population studies reveal that EFs become ‘online’ around the age of eight (Ardila & Rosselli, 1994), and age-related improvements in EFs occur rapidly from late childhood into adolescence. Adult levels of performance on EF assessments is reported to be attained between the ages of 12-15 (Diamond, 2002; Huizinga et al., 2006), and continue to improve into young-adulthood, albeit at a slower rate (Huizinga et al., 2006; Zelazo & Müller, 2002).

The results from Chapter 5 revealed that the majority of the improvements in EFs occurred throughout the ages of 10-15 years of age, aligning well with the ages reported in the general population curves (Diamond, 2002; Huizinga et al., 2006). In addition, steady yet considerably smaller improvements in EFs continued into early adulthood, demonstrating the similarities with the general population curves (Huizinga et al., 2006; Zelazo & Müller, 2002). In agreement with Chapter 3, there is little evidence to suggest that a dose response relationship exists between playing sport and EFs, as no changes to the natural trajectories of EFs were observed. However, the reported plateau and slight decrease in EF performance observed in Chapter 3 was not able to be confirmed in the longitudinal analysis of Chapter 5. Players > 21 years old were excluded from the study due to the low density of the sample for each age cohort over 21 years (i.e. between 22-36 years, n = 52 individual players), and therefore Chapter 5 could make no further confirmation on the trajectories of athletes after young adulthood with regards to cognitive decline.

Together, Chapter 3 and 5 dispute the previously described relationship between EFs and football performance, given the similar developmental trajectories that can be found in athletes exposed to high-level football training and those found in the general population. The large variation in the developmental curves of EFs observed in the athletes in both Chapter 3 and 5 provides an insight into the unique developmental trajectories of every athlete, whereby eluding to the concept that there is not a ‘one size fits all’ approach to

EF development between athletes, nor is there evidence a specific cognitive profile required to compete at a high level.

As there is no clear pattern of older athletes requiring higher levels of EFs to perform at a high level, this further supports the threshold hypothesis that natural abilities share with a competency. Although this threshold effect had not been previously investigated in sport, inferences were made in Chapter 1 using external research outside of a sporting domain to insinuate on the relationship between other natural abilities (i.e. IQ) and future success in competencies (Baird, 1985; Gagné, 2004; Terman & Oden, 1959). Therefore, we may also expect that the threshold hypothesis exists with EFs and sport, where as long as an athlete possesses a reasonable level of EFs, they could also achieve success in a sporting domain. This is in line with other natural abilities such as IQ's effect on creativity, where intelligence may increase creative potential only to a certain degree (between 115-120 IQ points), and any further expression of intelligence above the threshold did not correspondingly also increase creativity (Jauk et al., 2013). It should be noted that this dissertation only proposes evidence in favour of a possible threshold of EFs required to compete at a high level, yet the true threshold remains unknown and opens a new avenue for future research.

Although neither Chapter 3 nor 5 could not confirm that athletes throughout their development of expertise relied less on their EFs with more experience, the results could not also support that a high level of EFs were required to be within each elite age group. Yet if the professional adult athletes are suffering from either a plateau or slight decrease in their cognitive abilities, this further supports that adult athletes must progressively rely on their domain-specific experience in order to continue to compete at a high level despite their natural abilities declining.

A further explanation that may explain how football athletes are able to continuously play in spite of a decline in their generic cognitive abilities may lie within the definition of EFs. EFs are a conscious process that is involved in goal-orientated behaviour (Diamond, 2013). However, one large theoretical barrier that contradicts the use of EFs in the decision-making process in sport comes from the theory underlying the expert performance approach, first discussed in section 1.2. It is heavily supported by literature in many domains that expert decision-making in high fidelity environments largely bypass cognitive decision-making processes, relying more on non-consciously made intuitive decisions that require little to no cognitive effort (Belling et al., 2015; Kahneman & Klein, 2009; Travassos, Araújo, et al., 2013).

For instance, consider the amount of cognitive engagement required on first day of driving a manual car versus how little attention people require to drive after a few months or even years of driving. Other examples are the concentration required while learning to play an instrument versus expert musicians being able to sing concurrently playing a piano without looking at the keys. Similarly, in sport, young athletes learning a skill will dedicate a large amount of cognitive effort to complete the same task that experienced athletes can do with little or no conscious thinking (Hatfield & Kerick, 2007), freeing up their attention to be allocated on other environmental cues. There appears to be a pattern of the early stages of learning requiring high-cognitive engagement in the decision-making and control of movements that progressively switches to more non-conscious processes and more reliance on automatic processes.

"When I'm on the field sometimes I don't know what I am doing out there. People ask me about this move or that move, but I don't know why I did something, I just did it."
Hall of Fame American football player Walter Payton (Katwahla, 2016, pg 92).

Thus, there is a conflict between the theories of cognitive engagement in sport. The cognitive component approach states that EFs are important throughout the career of athletes (Verburgh, Scherder, et al., 2014; Verburgh et al., 2016; Vestberg et al., 2012; Vestberg et al., 2017). EFs are a conscious process and suggests that athletes are reliant on a consciously controlled processes to make the decisions during a match, allowing athletes to update and learn from their mistakes. If athletes are relying on their autopilot to control their decisions, they risk becoming too predictable in-game and making a mistake due to not paying enough attention. Opposingly, the expert performance approach states that experienced athletes have little or no reliance on their conscious processes during the majority of their decisions or reasons for action, allowing them to free their attention to more important areas of the environment. Moreover, athletes often report that their motor reactions evolved from a given situation without any consciously controlled decision-making, particularly under time-pressured scenarios, avoiding 'paralysis by analysis' (Kibele, 2006).

It is difficult to confirm any objective amount of attention dedicated to making a decision or carrying out the movement. Not all activities are equally as cognitively challenging across each individual (Diamond & Ling, 2018). EFs may have an inverse relationship with expertise, being the more skilful you are at the sport and as a proxy for more developed perception-action coupling, the less requirement of EFs within the decision-making process. "Once one is really good at something, one generally uses their prefrontal cortex and EFs less (expect if there is a change or something unexpected happens)" (Diamond & Ling, 2018, pg. 14).

One may argue (those within the cognitive component approach) that Diamond's quote on the requirement of EFs does not apply to playing sport. Sport characterized by ever-changing environment that are complex, rarely two situations that are similar, and is full of unexpected events. Unlike playing a musical instrument or completing a sport specific technique in isolation where the environmental conditions are relatively stable as per the studies that were included in Diamond & Ling 2018's review, a football match continuously presents challenging and new opportunities, which is specifically when EFs are allegedly most engaged.

Diamond and Ling's statement, however, is supported by Ericsson's widely known research on expertise (aligned with the expert performance approach), stating that an athlete's EFs are circumvented by experience (Ericsson et al., 2018). Ericsson and colleagues have argued for many years that domain-generic abilities, such as working memory, impact performance only initially during training where domain-specific experience is lacking. Progressive exposure to specific practice aimed to enhance their sporting performance (i.e. deliberate practice) has been theorised circumvent any limitations in domain-generic abilities, and thus a higher reliance on sport-specific abilities are used in the decision-making process, including pattern recognition, attentional control, information processing on task-relevant cues, amongst many others.

A quarter of a century ago, Ericsson and Charness (1994) argued that working memory capacity would only influence performance in the early phases of training, where athletes have not yet built up their domain-specific knowledge base – possibly <12 years old when domain-specific abilities showed no improvements in the longitudinal analysis (revisit

Figure 9). When the brain maturity is reached (i.e. early adolescence) and situations that involved implementing domain-generic abilities are working at threshold levels, subsequent development of domain-specific abilities can be induced by more experience in sport that would further contribute to performance improvements (Li et al., 2004). Indeed, more experienced athletes appear to be able to bypass their natural cognitive processing limitations such as their limited working memory capacity by storing and accessing sport-specific knowledge structures within their long-term working memory (Ericsson & Kintsch, 1995). This affords the gradual improvement of decision-making skills in experts, despite the limitations of its underpinning domain-generic abilities.

On the contrary, other research groups have contested Ericsson's view on an individual's ability to circumvent natural abilities with increased expertise Hambrick, Macnamara, Campitelli, Ullén, and Mosing (2016), stating that Ericsson has largely disregarded the fact that deliberate practice only accounts for 18% of the variance associated with high levels of performance (Macnamara et al., 2018). Therefore, 82% of the variance to explain how athletes have attained elite level status remains unaccounted for and provides evidence against the previous claims of the strength between deliberate practice and successful performance. Therefore, these results have therefore maintained the interest in pursuing to understand what constitutes the large amount of unexplained variance; and where domain-generic abilities may help to contribute to why some athletes reach the highest level of attainment of their sport and why others do not. The large unaccounted variance provides support for the continued investigation into what variables contribute to performance in sport, including differences in cognitive abilities to help explain the variance (Hambrick et al., 2016).

Seemingly, in order to overcome the lack of studies investigating the relationship between athletes domain-general and domain-specific perception-action coupling abilities (Furley & Wood, 2016), Chapter 5 further aimed to map out the longitudinal development using various assessments that presented varying levels of perceptual information or action fidelity to understand how these abilities develop with age and as a proxy for increased experience. As previously mentioned, one aim of the study was to understand how EFs developed over the development of athlete from late childhood to early adulthood (10-21 years old). Alongside the collection of EFs, domain-specific assessments were also measured and included in Chapter 5. This allowed for the simultaneous recording of the development of athletes' domain-general and domain-specific abilities throughout their attainment of expertise in football, which has not previously been conducted. In order to investigate the effect of age on the various assessments, two latent constructs were first created that represented both the expert performance approach and the cognitive component approach to examine an athlete. This distinction was based on how the perceptual information provided and the sport-specific nature of the action required. This subdivision reflects the general understanding of practitioners who use assessments that have a high face validity with football, rating an assessment that looks more like it has to do with football to be more sport specific it is (i.e. having a high face validity).

The first latent construct was 'domain-generic' assessments, which encompasses the EF assessments. These assessments, as demonstrated in Chapter 1, 3 and 5 attempted to measure the general cognitive abilities of the athletes by presenting non-sport specific information within a completely decontextualized environment from sport (i.e. sitting in a laboratory in front of a computer responding to colours and shapes and pushing buttons on a joystick). The longitudinal analysis demonstrated that domain-generic abilities developed at the fastest rate between late childhood into adolescence (10-15 years old), and slower yet continuous developments of EFs were observed into early adulthood.

The second latent construct was 'domain-specific' abilities and were measured using the Footbonaut and the Helix as these assessments were believed to be more sport-specific due to the assessments attempting to replicate the both the perceptual-cognitive and physical demands of the game, as demonstrated in Chapter 4 and 6. Although the onset of growth occurred onset two years after the onset of domain-generic abilities at the end of late childhood (i.e. 12 years old), the development of domain-specific abilities also rapidly evolved until around the age of 15 years old. Thus, the two developmental trajectories display similar growth traits prior to reaching adolescence.

Yet contrary to the hypothesis in Chapter 5 that expected improvements in sport specific abilities to be linear alongside increased years of engaging in sport specific experience, a performance plateau was observed in the assessments of the Footbonaut and the Helix; where any experience past the age of 15 years old did not seem to in turn improve the players' performance on these sport specific tests. Possible factors that may have contributed to the observed plateau in the football-specific curves are later discussed in more detail in section 7.1.4.

Perhaps in sport, it can be expected that both abilities contribute towards the decision-making process. Both developmental curves of domain-generic and domain-specific abilities appeared to grow in similar fashion from late childhood into early adulthood in athletes documented in Chapter 5. Possibly each decision is a situational-dependent combination of both systems using various levels of intensity in order to make the correct decision, and relies on whether the athlete picked up the required information to foresee the probable future events unfolding, or is caught off guard to an unexpecting play and must consciously reconsider his playing style. Both an athlete's domain-specific abilities that are developed over years of engaging in the sport itself and domain-generic abilities that appear to be largely heritable are required to make decisions in sport. Evidence in favour of this dual-system is reported during the development of working memory into adolescence, resulting in a better ability to perform more complex tasks, control distraction, and be more adaptable (Furley & Wood, 2016). In turn, abstract thought (i.e. creativity) and decision-making benefit from a more efficient and flexible working memory system (Luna, 2009) and would be expected to lead to better in-game decision-making performance (Voss et al., 2010). This is supported by a study in ice hockey that reported athletes with a better working memory capacity (i. e. a domain-generic ability) were better able to adjust their decision-making behaviour to the situational demands of the game (i. e. a domain-specific ability) (Furley & Memmert, 2012). Contrastingly, athletes with a poorer working memory capacity more often carried out coaching instructions despite them not being appropriate for the specific game situation (Unsworth, Heitz, Schrock, & Engle, 2005).

Therefore, more studies are required to investigate the role of EFs throughout the attainment of a skill, specifically in environments that continuously challenge the individual. It is not yet known to what extent expert athletes are using EFs in order to perform in a game, and at what level of expertise – if any – throughout the becoming an expert do athletes rely less on their EFs in order to make decisions within the game.

Future studies must also incorporate the possible explanation for another likely relationship between nature vs. nurture debate in EFs and athletes, stemming from the common saying ‘success breeds success’. The saying can be interpreted as athletes that have naturally high genetic EF abilities that developed intensely in early childhood may have an early advantage over their peers who possess lower EFs and are not yet able to compensate with their other undiscovered/undeveloped external assets (i.e. future height or power). This early advantage of young athletes being able to outthink their competition may in turn heighten their motivation to pursue their training and even increase the intensity to which they train; by enrolling into a formal institution such as a higher-level academy. Additionally, the young athletes who are excelling tend to get more joy from playing, and also receive more supervision from coaches and parents alike. This emotional investment may improve EFs (Diamond & Ling, 2016, 2018). It may be a reciprocal cycle, where individuals with higher natural abilities (see Figure 2) may become high-level youth athletes more often due to their early success. Their subsequent development in their actual football-specific skills from prolonged exposure to training from an early age further improves their chance of staying in a high-level of competition throughout their adolescence (Baird, 1985; Gagné, 2004; Jacobson & Matthaeus, 2014). This phenomenon is also prevalent in sport with other genetical factors such biological maturity status being a natural size advantage in youth athletes (Hill, Scott, Malina, McGee, & Cumming, 2019).

In sum, it appears that the use of domain-generic assessment tools to predict future talent has many limitations, and the studies within this dissertation go against the current body of evidence that advocates a stronger relationship between domain-generic abilities and football performance. A more detailed discussion regarding the practical implications of domain-generic assessments are in section 7.3.1. In line with the more heavily supported expert performance approach, more consideration should be placed on measuring athletes’ sport specific skills in assessments that are as closely related to their domain as feasible.

7.1.4 Representative task design: revisited

The importance of using highly representative environments in order to assess athlete’s true football specific skill was introduced in Chapter 1 under the expert performance approach, and the primary aim of Chapter 4 was to investigate the reliability and validity of a new football-specific tool that attempted to closely mirror the serial coupling of perception and action experienced during football match play. A large cohort of youth football players (U12-U23's) underwent skills testing in a football skills assessment task, the Footbonaut. The main finding of the study was that although the Footbonaut was able to show trends of improvement progressively in older athletes, there were no other significant differences observed between players in the U15-U23 categories.

A possible reason for the lack of discriminant validity of the tool after adolescent players (i.e. >15 years old) may have been caused by key perceptual qualities that were missing to make this test truly representative. These findings were also confirmed in the longitudinal analysis of Chapter 5 that athletes' performance on both the Footbonaut and Helix plateaus at a similar age. The Footbonaut yields a high action component but not a highly specific perceptual component to football, whereas the Helix provides the reverse, a football specific perceptual component but with no associated action required. Hence, the specific perceptual information may not have been adequately coupled with a sports specific action in either assessment (Pinder et al., 2011) and therefore may explain why the expected increase in performance with increasing football-specific experience was not observed in Chapter 5. Consequently, in order to improve on the methodology of the Footbonaut, various avenues were explored in Chapter 6.

The Footbonaut attempts to expand upon previous skills assessment tasks that are commonly used assessment tasks (Ali, 2011), training two of the most relevant skills in football: the first touch (Thomas, Fellingham, & Vehrs, 2009), and short passing. It has been previously reported that a short pass preceded 47% of goals scored by direct shots in the 2006 FIFA World Cup (Sajadi & Rahnama, 2007). As previously stated in Chapter 1 section 1.2.1.1.1 (the editorial), it is the duty of the sport scientist to critically analyse the equipment that the club is using in order to understand whether the club's staff can trust the results to make informed decisions about players' performance. The Footbonaut has many strengths including its ability to be standardized across every trial per player and between players, the accuracy of the gate sensors that produce speed and accuracy data, and the benefit for it to a flexible machine where almost every feature can be manipulated to vary the difficulty. Yet as the previous research conducted has demonstrated that the specific use of the Footbonaut within Chapter 5 showed limited observable differences in skill performance from players after the age of 15, this tool might be better classified as a non-representative setting that includes a highly representative football action component. Consequently, despite the best attempt to use assessments that attempted to replicate the demands of football, the difficultly in replicating the perceptual demands of a real match in a laboratory-based setting remains. Thus, the change in classification towards the Footbonaut acknowledges the limitations of the Footbonaut, and further attempts to re-invent this tool (and others that succumb to the same fate) that are currently in the possession of the club has merit. Introducing new technological components can help to advance the usefulness the Footbonaut rather than discarding its use and resort to finding a new tool on the market, known as creative destruction. Seemingly, Chapter 6 demonstrates the incorporation of two different pieces of technology within the Footbonaut in order to improve the understanding of what are the necessary sources of information that players receive and utilize in order to formulate an appropriate action.

The first attempt to help improve the Footbonaut's useability in research and practice was the introduction of stroboscopic glasses demonstrated in Chapter 6a. This study aimed to provide further details about how athletes sporting skills are heavily reliant on the visual information that they perceive in order carry out the action, and that this reliance increases throughout the attainment of expertise. In summary, skilled athletes demonstrated larger decrements in performance compared to lesser-skilled participants when subjected to restricted visual conditions. This study demonstrated that using the glasses to change the perceptual demands placed on the athlete rather than changing any attribute of the actual test may be a potential fruitful avenue for practitioners to use if restricted with under-representative or assessments that are not challenging for more skilled players. These glasses also help to discriminate between the skill levels of each player, as shown in another study using these glasses to sperate skilled groups of dribblers (Fransen et al., 2017).

Another impression from Chapter 6a is that it is clear that athletes require constant visual information in order to act appropriately in their environments. Chapter 6a states that as visual information is important, but the study lacked any ability to make inferences on how the glasses may have disrupted the spatial attention allocation. For example, it was theorized that the more skilled athletes' normal search pattern of receiving visual information from the gate, the approaching ball and the location of the proceeding target may have been disrupted as a consequence to the limited visual information; however no objective measure was integrated in order to confirm such proposals. Therefore, this insinuated towards measuring the potential differences in visual exploratory actions that both skilled and less-skilled players use in order to perform in the assessment task. Focusing on understanding the required input of information leading up to an action would allow for a better analysis of the underlying mechanisms that contribute to performance in the Footbonaut.

The second attempt to improve the useability of the Footbonaut is reported in the final part of this thesis, discussing a recent study conducted by McGuckian and colleagues (in press) in Chapter 6b. Although the major aim of the study by McGuckian and colleagues (in press) was to examine the VEA between young and older athletes as a contributor to performance in the Footbonaut, this study nicely related to the theme of Chapter 6. Recent research has reported that a more active visual scanning behaviour (i.e. higher frequency of head movements with the purpose of exploring the surrounding environment) prior to receiving the ball lead to faster performances in the subsequent action (McGuckian, Cole, Chalkley, Jordet, & Pepping, 2018b). Yet as this study was conducted in a laboratory-based setting using computer monitors and without participants physically kicking a ball (kicking a sports cone was used instead), the laboratory environment may have also underrepresented the dynamic performance environment experienced by players in normal match conditions (Dhami, Hertwig, & Hoffrage, 2004) and reduced the effects of the study. Therefore, an improvement in the methodology of investigating VEA was to incorporate this technology in the Footbonaut, where athletes have to use a highly representative action component to respond to the visual stimuli in a more representative environment. Thus, the incorporation of IMUs to objectively record the scanning behaviours of athletes within the Footbonaut may allow researchers to understand on a deeper level the reciprocal nature of the relationship between perceptual-cognitive skill and football-specific technical skills (McGuckian & Pepping, 2016); and how this relationship is developed over the skill level of players.

Thus, the final part of this thesis discusses a recent study conducted by McGuckian and colleagues (in press) in Chapter 6b, where this study reported clear age-group differences in head scanning frequency are apparent in the Footbonaut between skilled and less skilled athletes. The differences in the visual exploratory actions with and without possession of the ball between U13 and U23 players suggests that older players (U23's) explore their surroundings more extensively before gaining possession of the ball, which translates in them exploring less once they are in possession of the ball. Contrastingly, younger players (U13's) explored their environment more when they received possession of the ball as opposed to beforehand, restricting them from having a pre-planned action once the ball is received, and in turn slowing their overall speed in the Footbonaut (McGuckian et al., in press). This new and fruitful area of research for measuring the VEA in football players allows for a further understanding on how athletes use visual information in order to prospectively control their subsequent actions when receiving the ball in the Footbonaut, and may provide beneficial insights into how these exploratory actions transfer into the real match-play. For example, athletes that do not use high amounts of VEA in the standardised environment of the Footbonaut may also indicate a lack of exploratory behaviours on the pitch, although this generalization has yet to be supported by research. Aligned with their hypothesis, McGuckian and colleagues (in press) reported that the older players completed passing actions more quickly than younger players in the Footbonaut. This finding was not novel, aligning with the findings of age-group performances in the Footbonaut found in Chapter 4. Of greater interest to this investigation is the factors that contribute to this difference in performance, in particular the VEA variables that help to explain performance differences in performance within in a skills assessment task.

The study by McGuckian and colleagues (in press) nicely complimented this dissertation, by demonstrating that new technology can improve the output that can benefit both researchers and practitioners alike. For example, these sensors can be used for training and talent identification purposes when incorporated into the Footbonaut. Additional research in youth football players supports this claim, reporting that players who visually explored more before receiving the ball were more likely to play a successful pass forward, play a pass into the attacking half, and turn with the ball compared to when they had not visually explored (Eldridge, Pulling, & Robins, 2013). Interestingly, this technology has yet to be implemented with athletes in the Helix, but may provide an interesting avenue of future researchers to explore how athletes use their VEA to be able to keep track of multiple players on the field.

Together, McGuckian et al. (in press)'s study alongside with introduction of the stroboscopic vision glasses contained in Chapter 6 attempted to demonstrate that the use of the Footbonaut appears to be a good steppingstone to improve the methodologies of other streams of research. For example, Fransen et al. (2017) had players dribble a ball through a pre-set course made up of cones inside a gym. In this study, a large action component was required (i.e. dribbling a football), but no perceptual component (i.e. a gym environment with no perceptual cues to dictate action was provided). Contrastingly, McGuckian and colleagues' research was based in a laboratory environment with computer screens surrounding the athlete (McGuckian et al., 2018a). There was a large perceptual environment (environmental cues that dictated action), but the action component was missing (no physical action was required). Seemingly, using the Footbonaut was an attempt to advance the methodological limitations of both the different areas of research.

In sum, sport scientists and researcher alike should be strict in evaluating the assessments that a team is using to measure their athletes, as it is important to have objective trust in the assessments rather than succumbing to the bias associated with owning the tools and having them be already incorporated into regular testing. However, if the assessments are shown to be lacking in certain characteristics that lessen their ability to effectively assess athletes in high fidelity environments (i.e. findings of Chapter 5), this does not mean that they are redundant. This chapter should serve as a demonstration of practical solutions to help adapt the existing equipment to better match the perception or action demands of football.

7.2 Limitations of this dissertations

This thesis presents novel research with substantial theoretical, methodological and practical contributions. However, there are noteworthy limitations to each study's methodology and design that should be considered when evaluating the findings. Many of these limitations are a product of such a novel research area. The limitations of this thesis, as outlined below, should be addressed with further development in this research area to provide an even stronger evidence base.

i. The experimental design of the Footbonaut used in Chapter 4 and 5 may not have provided the appropriate environmental information to participants that is required to maintain representative perception-action couplings found in live match-play. In particular, the constraints of the Footbonaut does not require participants to respond to real players or shoot at real goals in order to complete the task. High fidelity of environmental cues is an important component of action in a live football situation, and the participants may have exhibited different football behaviours compared with if they were immersed in a true game-like environment. However, given that this limitation was acknowledged within Chapter 5, the proceeding Chapter 6 was specifically aimed at findings a solution to this limitation.

ii. The dataset used in the studies except for Chapter 6a comprised of participants belonging to only a single club in Germany. As a result, the findings are representative of the players involved in the studies at the time of data collection. It may be possible that findings may differ in samples with different individual players and team characteristics, such as training background, playing philosophies and strategies. However, given the uniqueness of all equipment used in this study, it is difficult to confirm such statement. Only five Footbonaut's exist in the world, whereas there is only one Helix. Furthermore, the EF battery of tests used is a unique battery used by the club, and it is to the author's knowledge that this club is the only club that was measuring EFs at the time in Germany.

iii. For the 1st year of data collection of EFs, players were tested in a large open room while the building was undergoing construction where the new EF testing battery was held. Despite having staff present at all times overseeing the data collection, it may have been more possible for players to get distracted by others that were watching and waiting for their turn, and therefore this may have influenced their performance. However, from the 2nd year onwards following the construction of the new building, the EF testing room was used where players had isolated booths to complete their tests on and where no distractions were possible.

iv. Specifically, in Chapter 6b, participants were required to wear an inertial measurement unit (i.e. the head movement sensor) that was placed in a headband while participating in data collection. While participants were not explicitly told directly what the device was collecting, it is likely that participants had some understanding of the purpose of the device. Therefore, it is possible that their exploratory actions may have changed in response to the experimental nature of the data collection in the Footbonaut, being that if they knew head movements were being measured, they may have changed their exploratory action. However, upon asking the players after their sessions about the technology, they reported no differences and mentioned frequently that they “forgot they were even wearing it”.

v. A sample from the general population was not assessed alongside the sample of high-level football players to be compared with on the EF assessments. However, a plethora of previous research within non-sporting specific populations has mapped out the developmental trajectories of domain general abilities (i.e. including EFs) allowing large inferences to be made. However, the inclusion of a control group is still an important step and recommendations on how to best overcome this limitation is stated in the following section 7.4.1. However, even if the relationship between sport and EFs is causal, it is difficult to measure due to all the confounding factors that might interfere with this relationship. This also is the case for the control group. Humans do not merely engage in sport. Other cognitively stimulating activities such as reading books, learning a musical instrument or playing games such as puzzles or cross words, amongst others, has also been shown to reduce the cognitive decline in older populations (Wilson et al., 2003); making the causal relationship between only sport induced effects and EF difficult to measure. Furthermore, every profession requires some type of cognitive engagement. For example, a person who enjoys playing chess or video games would utilize a similar process of cognitive abilities to inhibit distractions and make rapid decisions in goal-oriented activity. Even an individual who played piano throughout their youth would have relatively high levels of manual dexterity and motor reaction time which may influence their performance on generic ability tests. These non-institutional based, informal learning (i.e. leisure learning) activities may all have substantial contributions on performances within generic tests. Seemingly, this could influence the EFs of the control group, but also help to explain some of the inter-individual variation in EFs. Thus, simply providing control group participants with a sports-participation history questionnaire is not sufficient, and many other factors must be attempted to be accounted for in order to attempt to find suitable comparisons between athletic and non-athletic control groups.

vi. The majority of the assessments used in the current study were already being in use as performance assessments before the start of the thesis. Therefore, it is possible that there is a player bias selection of sample. For instance, previous athletes with less EFs or poorer Footbonaut scores may have influenced coaches' decisions for some players before and during the duration of data collection to not enter (i.e. talent ID) or be retained in the club. Therefore, one avenue to overcome this limitation is to have other teams with equal level of attainment complete the battery of tests.

7.3 Practical recommendations for applying domain-specific and domain-generic assessments in a high-performance football environment.

7.3.1 Domain-generic assessments

Despite the limitations listed above in section 0, football clubs and other sporting organizations alike have been using domain-generic assessments for many years in attempt to measure not only their own athletes, but also that of external players who may have the alleged cognitive potential to compete at an elite level. Over the years, the practitioners involved in implementing these assessment tasks have pursued the best practice to apply these tests in a high-performance environment. A combination of the previous research that was available before the start of the dissertation, the internal research studies that were conducted within the dissertation, and the many years of experience of the practitioners that have been at the club, has cooperatively influenced the way in which the data is collected, analysed, interpreted, and delivered to players and additional coaching staff. To express all forms of beliefs, an opinion piece was written together with the practitioners of the club in order to discuss the implementation of domain-generic assessments in a sporting environment and can be found in the appendices section 8.2.

In short, there currently exists a lack of agreement in the literature on whether EFs as a prognostic tool for football talent has practical validity. More longitudinal research is needed to understand if assessments of EFs are able to help practitioners predict talent in young athletes. For example, does assessing EFs have more value to help in the detection of potential talent from a heterogenous cohort that does not yet compete at a high-level (i.e. assessing a large group of school kids to find one that could be a good football player), or in the identification of the best performers within a homogenous cohort of already competing athletes (i.e. assessing which high-level academy players are likely to transition into adult-professionals)? Currently, no study has yet to demonstrate that athletes with higher EF scores become more successful in their sport. Pending further research, a current focus on EF development in the lower achieving athletes may be a more suitable use based on the findings within this dissertation considering the possible threshold effect of EFs on performance.

Furthermore, no gold standard currently exists on what the best practice is to measure EFs in athletes or in any other population for the matter. Questions such as ‘which choice of assessments are appropriate’ and ‘should there should be different assessments implemented within different populations’ remains undefined. It also remains difficult to predict with the current stage of the literature whether implementing an EFs testing battery will yield supportive or harmful results regarding the opinion of an athlete. The inconsistency of the literature with a large variety of populations, assessment choice, and inconstant results in the research has left both a large paucity of knowledge, but also provided an opportunity for more researchers and practitioners to act upon and to contribute to this area. With EF research being a relatively young area of research, the importance of EFs in sport remains widely unknown. Hence any interest by clubs to implement assessments of EFs of course is beneficial from a research perspective but should be highly cautious with over emphasizing their use in practice.

7.3.2 Domain-specific assessments

It has been a common methodological problem to find suitable assessment tasks that are applicable across all age levels. With vast differences in years of experience playing football, differences in physical, technical and skill abilities, makes it is possible that the assessments might be very challenging for the younger groups and too easy for the older age-groups (De Luca et al., 2003). This is demonstrated by Chapter 4. While possessing some discriminating validity, the Footbonaut did not distinguish between age groups after players reached adolescence. Despite this finding, this does not automatically rule out the Footbonaut as redundant. Sport scientists can use the current protocol in Chapter 4 in order to build a new design of the testing protocol that has an increase of difficulty suited to the increased level of skill demonstrated in the older athletes, after the age of ~15 years old has merit. This can be achieved by changing one of the many physical parameters of the Footbonaut, such as the speed of the ball being dispensed (i.e. > 50km/hr), using the 2nd top row of gates to pass the ball into or be dispensed from, changing the spin of the ball being dispensed, or the vertical angle to which the ball is dispensed from (i.e. $> 2^o$). Secondly, additional perceptual demands could also be implemented to increase the level of difficulty of the session. For example, the introduction of crowd noise could interfere with the acoustic signals, or the removal of the acoustic signal of where the location of the gate would force athletes to be more responsive to their environment.

With regards to the Footbonaut itself, it is unreasonable to advocate that other clubs should also invest in this specific tool due to its expensive price tag. However, at the core of the Footbonaut's design, it signifies that in order to measure an athlete's true skill capacity, the most ecologically valid environments must be used. The design of an assessment cannot be simply met with the concept that the more realistic the testing environment looks like to match play, the better it is to use. The Footbonaut is often portrayed as one of the best assessment tasks to measure athletes based on many of its realistic features reflecting actual football performance. But even the Footbonaut has many flaws that require amendments. Mainly, it is trial and error. But without a thorough and honest investigation into various forms of validity and reliability of the tools being used to measure athletes within each club, decisions may be made by erroneous data that can lead to a dangerous snow ball effect, having negative ramifications when using this data as a part of the decision-making process of players career at the club.

7.4 Recommendations for future research

This thesis has greatly developed research investigating the use of both domain-specific and domain-generic assessments in football. Despite the advancements within the current dissertation, the research in these assessments is still a developing area. To further increase the practical applications of this research and to extend this research to other areas, it is recommended that future research aims to build upon the work completed in this dissertation in several ways. The following list is not exhaustive, but the ideas discussed are likely to result in substantial practical benefits in a range of settings.

7.4.1 Adding a control group

A major limitation from the current dissertation was that no control group was used to compare the between-age group differences in EFs specific to the battery of tests provided to the athletes in these studies. In theory, a longitudinal analysis with repeated measures using both high performing athletes and a non-athletic control group is necessary to establish if there are any observable differences in the cognitive developmental patterns between groups as a result of engaging in sport for long durations. Potentially, research should look to design a study with a direct comparison of one group that plays sport at a highly competitive level, a group that is physically active but does not participate in a competitive sport, and a non-active group would be one approach to measuring the influence of sport and physical activity has on cognitive functioning.

7.4.2 Taking into account a compensation effect

In sport, many athletes have various strengths and weaknesses that work together to allow each athlete to be a unique player. One of the most famous examples is Lionel Messi, who compensated his shorter height with his outstanding technical and skill abilities. Generally speaking, a young student that is tall is more likely to do well in a sport such as basketball than a shorter student of the same age. However, the tall student needs still to be coached well and train hard to be great and would require many other factors such as good coordination, strength, and high motivation to consistently remain competitive after their height advantage becomes absolute in the following years. This may be true with other players and their EFs. As Chapter 3 reported a large variation of EFs performance within each age group, it would be an important avenue to understand whether the athletes that had worse EFs were better physically or had a stronger work ethic and mindset than athletes with higher and a faster onset of their natural cognitive abilities. Future studies should aim to conduct a variety of additional comparisons, such as how players with high and low cognitive abilities rank on other measures of performance, such as physical test (i.e. sprint and jump performances), maturation status, relative age-effects, psychological measures (rigour, grit motivation) and more detailed playing history questionnaires (i.e. years in a structured academy). Returning to the basketball example, it has been shown that good coaching can sometimes overcome deficiencies in players height. Baird (1985) notes the better the coaching athletes received, the lower the correlation between height and success in basketball. Therefore, if and how athletes with lower EFs compensates to remain competitive against athletes with higher EFs would be an interesting avenue to explore.

7.4.3 Attempting different grouping strategies

Although the studies within this dissertation support the notion that EFs are not a stable predictor of future success in football, the results were also not able to rule out the possibility that the youth athletes with the highest EFs do not have an early natural advantage against other players that would contribute to them becoming the future adult professionals (i.e. success breeds success mentioned in Chapter 7). This would require many more years of tracking players in order to confirm whether or not having higher EFs is an advantage, especially in the new age of football with ever-increasing mental demands. Yet in the meantime while these longitudinal studies are ongoing, additional methods of relating EFs and success could be conducted. For example, relating a player’s EFs to a coach’s subjective ratings of skill performance or correlating EFs performance with what coaches believe their potential to reach the future professional group is.

7.4.4 Sport-specific actions requiring executive functions

Computer-based EF assessments could have their criterion validity investigated by testing athletes in more sport-specific situations that attempt to stress certain types of EFs processes. The first example could be to design three different small-sided games and put them next to each other on the pitch (see Figure 11). Every two minutes, each athlete has to switch to the next the small sided game, which encompasses a new set of rules, tactics, teammates, and playing style required. Then, players would be assessed on their ability to immediately adapt to a shift in the playing environment, stressing the shifting mental processes. Are players able to do this? Would this (in)ability to be able to shift demands also be reflective on their cognitive flexibility measures from the computer-based EF measures?

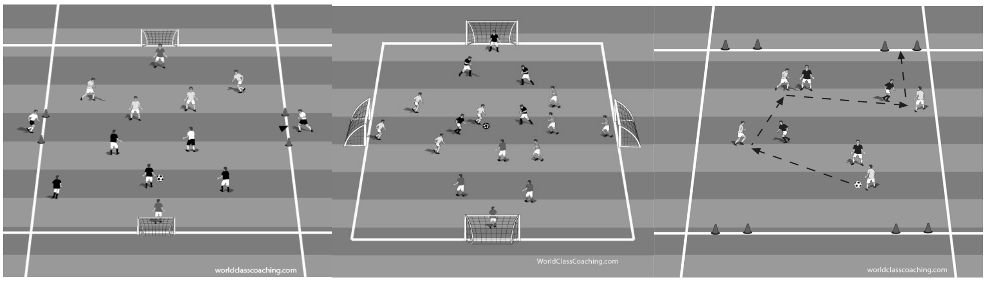


Figure 11. An example of side by side small-sided games on a field. Images sourced from: https://coachingdutchsoccer.com/dutch-style-4v4-small-sided-games/

The second example would be replicate the concept of the PCRTT and incorporate it into the design of the Footbonaut. As mentioned in Chapter 1 under ‘Preliminary investigation into executive functions: part 1’, the PCRTT has players respond to a visual precue to aid the players as to where the likely location of the yellow dot will appear. The task presents both congruent (i.e. correct information) and incongruent (i.e. incorrect information) precues that players either have to act on or negate. Similarly, in the Footbonaut, players already respond to congruent auditory and visual cues in order to aid finding the location of the gate to pass the ball into. It is possible to modify the protocol of the Footbonaut to have both congruent and incongruent auditory stimuli of where the ball should be kicked into, being that the target sound could come from a false target gate of the Footbonaut. Therefore, it is possible to then compare the results of the PCRTT with the Footbonaut performance to see if each player has similar good or bad performances on both tests.

7.4.5 Understanding external contributing factors

From discussing the results with many practitioners at the club, they note that there are many variables that may influence the EFs scores, such as levels of motivation, mental and physical wellbeing, amongst others. It has been anecdotally reported that these factors contribute to the players' performances on the day of measuring their abilities yet have not been scientifically accounted for. Therefore, in order to further understand to what extent these additional factors have on the assessment battery results, further research is needed. Potentially, players could conduct psychological questionnaires on the same day and have subjective ratings of wellness to support practitioners' claim.

7.4.6 Does injury influence executive function development?

To the authors' knowledge, no study has taken into account a player's injury status within their studies. Yet if engaging in sport-specific activity does in fact improve cognitive function (Verburgh, Königs, Scherder, & Oosterlaan, 2014), then not actively engaging in sport for a long period of time (i.e. > 8 months for an ACL injury) could also reduce cognitive function in the same manner. Although this remains speculative until further research is conducted, it is still recommended to keep a note within the database, similar to if a player received a concussion during the season (Collie, Darby, & Maruff, 2001).

7.4.7 Helix

Chapter 5 noted that the Helix (i.e. the multiple object tracking assessment task) was not able to differentiate significantly between various age-groups from U12-professionals. Seemingly, Chapter 5 also mentions how the representativeness of an action component was lacking. Anecdotally, a 360^{o} Helix is currently being developed within the club that participated in this study, and additional steps in order to make the screen interactive with a ball has been set in place. Furthermore, as mentioned in the editorial in section 1.2.1.1.1, there are already existing immersive and interactive assessment tools that have yet to have their reliability and various forms of validity confirmed. Therefore, researchers could learn from previous research in immersive assessment tasks in order to further their understanding of how representative task design is achieved using more specific perception-action coupling in the new Helix.

7.4.8 Threshold effect

It is clear that EFs are a component that plays a role in athletic performance, and that the new evidence from this dissertation supports that athletes may require a certain amount of EFs to compete at the highest level of play, which would explain why there are differences in high and low level athletes reported in other studies (Voss et al., 2010). Further investigations into defining the thresholds of perceptual-cognitive abilities required to perform at the highest level of football per each age group has importance. This research would require the comparison of athletes from each tier of football (i.e. 1st, 2nd, 3rd and 4th division of football etc..) to be compared against each other on each specific age group. With more data being collected yearly at the current club and the anecdotal understanding that many more clubs are introducing EFs into their teams' assessment batteries, there is an opportunity to begin to have a collaborative database to visualize what the 'average' EF profile of each tier of football looks like. Questions such as: 'Is there more intensity of expression (i.e. higher EFs) within the higher tiers of football?' should be explored. There currently are no specific thresholds, guidelines or a prerequisite 'EF profile' required for entrance to a certain level of play such as other jobs that have large benchmark data. For example, the physical requirements to enlist in the military are very clearly presented, and universities have clear grade point averages required to even apply for a position to study.

Possibly, the future of this area of research will be able to find trends regarding players' EF scores in their youth and whether they became future adult professionals or not. From these data, it may be possible to say that athletes who were in the upper ~40% of EFs performance relative to the norm at age *x* were significantly more likely to become future professionals than those below this percentile.

7.4.9 Applications outside of a high-performance environment

These findings could also be beneficial if extended into community level and broad-based participation groups, as yielding a higher level of EF intensity has been attributed to better quality of life (Diamond, 2016) and important throughout all stages of education (Moffitt et al., 2011). If future research demonstrates that sport nurtures improvements in EFs, possibly more likely in children (< 12 years old), then children that have demonstrated lower EF performances could use sporting interventions to improve their EFs rather than any computer-based training programs. This is supported by work from Diamond and colleagues who's work publicised sporting activities that are challenging and allow children to feel self-confident and emotionally supported can help improve EFs (Diamond, 2013; Diamond & Ling, 2018).

7.5 Conclusion

This thesis attempted to answer a question that was largely driven by practice regarding one core theme: what is the suitability of using both domain-generic and domain-specific assessment tasks in a high-level football environment?

With regards to domain-generic assessments, a series of studies were undertaken that cooperatively aimed to understand whether playing sport at the highest level of competition for each respective age group required athletes to have a high-level of expression for general cognitive abilities (i.e. EFs). Investigating whether EFs could help practitioners make more informed evaluations on young athletes in a holistic manner is valuable, given that EFs are a component in the decision-making process and share a high face validity with how athletes make decisions.

One preliminary study (Chapter 1), one mixed-longitudinal study (Chapter 3) and one longitudinal study (Chapter 5) investigating the relationship between EFs and football together reported evidence to conclude that higher expressions of domain-generic abilities did not appear to better contribute or explain better why athletes have attained the highest level of playing standards for their respective age groups. Older athletes who were either approaching the adult professional level or the adult professionals themselves did not display any unique difference in the intensity of EFs compared to a normal range based on the general population data reported in external research. As the developmental curves of high-level football athletes' EFs appear to be parallel to that of the general populations, this is indicative that the improvements of EFs of athletes throughout their adolescent phase may be largely attributed to the normal maturation of the central nervous system rather than any sport-induced developments. This dissertation also demonstrated the relationship between EFs and success in football is similar to how other natural abilities contribute toward the success in other competencies; being that EFs appear to suffer the same fate under the threshold hypothesis. Athletes may require only a certain amount of intensity within their EFs in order to play the sport at the highest level, yet any further expression after the threshold is unlikely to further benefit improvements in their performance.

This dissertation has confirmed in sport the well-established understanding (outside of a sporting context) that a weak relationship exists between measuring domain-generic abilities (i.e. EFs) and relating them to domain-specific talent or achievements (i.e. success in playing football). The results from the current studies demonstrates that although natural abilities are a part of the foundation that a processing the cognitive demands of playing football is built upon, there continues to be little evidence to support that a transfer exists between these two constructs (Gagné, 2004). In other words, there is no direct bilateral relationship between playing football and improving a player's core cognitive abilities. This has strong practical applications, as it questions the capacity that using EF assessments has on making any inferences on the future end points of EFs in older athletes based on their youth EFs performances.

The studies conducted within the current thesis went against the last decade of research of EFs in football. Currently, the danger lies on researchers over-emphasizing their findings regarding the importance of having higher EFs to perform at a high-level without the supporting literature (Huizinga et al., 2006; Verburgh, Scherder, et al., 2014; Vestberg et al., 2017). Previous literature may have over-estimated the association between sporting performance and EFs, using cross-sectional data and small sample sizes as evidence in support of the proposed high practical validity for use in talent identification absent of longitudinal studies to confirm such propositions. This dissertation's novel findings demonstrate that EFs developmental trajectories for each individual appear to be too variable in order to rely on as a measure to predict future talent in football. It also appears that the developmental trajectories throughout all stages of development of EFs prior to adulthood are too varied between players to make any possible inferences on what an ideal 'cognitive profile' of an elite athlete requires.

This thesis does not deny that the concept of investigating whether EFs could help practitioners make more informed inferences on young athletes' future performance potential is not useful. In fact, multiple future research avenues have been proposed that will continue to improve gaps in the research on the role that EFs play in sport. Many limitations existed throughout the studies included within this thesis and further research to improve this area of research is warranted.

With regards to domain-specific assessments, the current thesis had the intention to document how athletes progressively perform in a new football specific skills assessment test. However, despite the best attempt to utilize the newest technology, the assessment tasks were found to be under-representing the normal environment in which an athlete normally performs their skill in. The findings contained in Chapter 4 and Chapter 5 raised an issue that reflects a greater problem that is common in a sporting domain. Many football-specific protocols are based on a general understanding that the more an assessment looks like it has something to do with football, the more specific it is supposed to regarding the actual demands of football (i.e. having high face-validity versus confirming its construct validity). However, it is our role as practitioners and scientists to look past the flashy uses of technology and price tags to ensure that these new high-tech tools abide by the crucial pillars of what constitutes an accurate assessment of a skill. Several forms of a tool’s validity and reliability should be conducted in order to understand whether the tools that are being used are providing trustworthy results. Upon the evaluation of the assessments used, this thesis demonstrated many alternatives to improving the assessments at hand in order to improve the usability of their outputs and demonstrated that we should not fall into the textbook example of creative destruction; whereby the old technology gives way to the new. Rework rather than replace. Therefore, a new question was put forth and extended the research within this dissertation into Chapter 6, being how to best utilize and adapt the existing infrastructure to continue to examine perception-action coupling demands of football. The infrastructure of the Footbonaut and Helix still has many strengths and practicality for research and training athletes in practice, but it is important to also consider their limitations when interpreting the results from athletes being tested within them.

Taken together, the information contained in this dissertation is especially pertinent given the previous decade of domain-generic research that has conveyed a more positive outlook on the potential of EFs within sporting environments; while expensive training tools with flashy displays of technology can appear deceivingly accurate without the science to support such claims. This thesis offers scientific merit given the limited amount of domain-generic related research in high-level football populations, and no scientific studies having previously examining the Footbonaut or Helix. Lastly, this research could potentially be of importance to researchers, coaches and practitioners to factor in considerations of whether their tools are truly measuring what they are intended to, and to self-evaluate the testing battery that is used to assess the athletes both within their teams and external athletes within talent identification programs in order to ensure that their data is trustworthy.

"There are a million ways to achieve success, but you have to meet some criteria."
Chancelor Jonathan Bennett.

"Many things are necessary, but not sufficient for success."
James Clear

Chapter 8: Appendices

8.1 Preliminary study: Age-Related Differences in Executive Functions Within High-Level Youth Soccer Players.

The preliminary study detailed in Chapter 1 has been accepted for publication. The full reference of the manuscript is:

Beavan, A., Spielmann, J., Mayer, J., Skorski, S., Meyer, T., & Fransen, J. (2019). Age-Related Differences in Executive Functions Within High-Level Youth Soccer Players. *Brazilian Journal of Motor Behavior*, 13(2), 64-75. https://doi.org/10.20338/bjmb.v13i2.131

8.1.1 Abstract

Background: It is less common for athletes to be assessed on their ability to detect and process implicit sources of information. Aim: This study aimed to investigate age-group differences in executive functions within youth football players, with the inclusion of a new implicit precued choice response time task. Method: Seventy-four male football players: U12 (n=15), U13 (n=17), U17 (n=21) and U19 (n=21) representing a representing a youth academy of an elite German Bundesliga club participated in this study. Players conducted a battery of computer-based cognitive function tests: a precued choice response time task (PCRTT), a stop signal reaction time task (SSRT), a multiple-object-tracking task (Helix), and a reactive stress tolerance task (RSTT). Results: The MANOVAs revealed a multivariate effect of age group on the RSTT (p<0.001, ES=0.38) and the SSRT (p<0.001, ES=0.20). A one-way ANOVA revealed an age group effect for response accuracy in the Helix (p=0.01, ES=0.14). Lastly, a within-subjects effect of congruency on the PCRTT (p<0.001, ES=0.41) and a between-subjects effect of age group (p=0.008, ES=0.15) was observed. Interpretation: The results provided support for including an implicit precueing task, while the overall testing demonstrated that the magnitude of the increase in executive functions between ages was greater across the younger age groups compared to the older age groups.

Keywords: Football, Cognitive, Inhibitory Control, Implicit Precue

8.1.2 Introduction

In a sporting context, executive functions (EF) are a sub category within the theoretical frame work of the cognitive component approach, and are often described as 'game intelligence' (Stratton, 2004). Vestberg et al. (2012) first noted that the existing body of research lacked understanding of the importance of general cognitive abilities within an athletic population. The authors proceeded to test high and low division adult football players on a series of non-sport specific cognitive function tests. The results revealed that football players outperformed the norm group for both men and women, and high division players outperformed the low division players. Since Vestberg and colleagues' paper on EF in sport, interest in measuring EF has grown.

One EF that talented football players consistently outperformed their lower-level counterparts on is response inhibition (i.e. the suppression of an ongoing motor response) (Verburgh, Scherder, et al., 2014; Vestberg et al., 2012), among others. Thus, enhanced response inhibition may be a contributor to successful sporting performance in more talented players across all age groups, and therefore advocates for more research to investigate this EF. The importance of response inhibition in sport may be attributed to the role that it plays in the decision-making process (Weinberg & Gould, 2014). The ability to inhibit a response results in players making fewer errors by being able to suppress acting on a decision; which is typical in football when a defender suddenly guards the intended receiver of a pass, and a new decision must immediately be created. Response inhibition in the EF research has commonly been assessed using simple or two-choice motor response tasks (Chan, Shum, Toulopoulou, & Chen, 2008). However, a simple motor response may not be representative of the stimulus-response a team-sport athlete encounters in-situ. Accordingly, a multiple-choice motor response task test may better reflect performance, as players must decide rapidly which decisions to act upon and which decisions to suppress while presented with a variety of options (Travassos, Araujo, et al., 2013). Moreover, not only is the task complexity simplified, the current response inhibition tests such as the stop-signal reaction test are explicit in nature. It may be speculated that the vast majority of stimuli which athletes are exposed to are hidden within the sporting environment (i.e. implicit rather than explicit), as it is impossible to consciously attend to every stimulus. Many stimuli go unnoticed during a game that may non-consciously change and/or challenge the athlete's sporting performance (Kibele, 2006). Therefore, the development of a new EF test that measures the impact that implicitly perceived visual cues on response time has value.

Understanding the influence that non-attentively perceived cues have on motor performance requires the contribution of the paradigm in cognitive science known as 'precueing'. Precueing is the effect that a presented stimulus has on participants' subsequent decision-making or motor behaviour, albeit an explicit or implicit stimulus (Posner, Snyder, & Davidson, 1980). A precue can influence a decision at a non-conscious level, leaving the participant with no subjective experience of having their decisions altered or to some extent, delayed (Kibele, 2006). For instance, in an attempt to prepare the player in possession of the ball for the movement that will occur next, a teammate may point towards their intended direction prior to the initiation of a run. However, whether the player in possession of the ball consciously or non-consciously registers the teammate's hand gesture prior to the run is not always certain.

The first studies on the effects of advanced visual information have demonstrated that if this information provides accurate information about the subsequent stimulus (congruent), it improved reaction times in comparison to non-cued trials (Posner et al., 1980). Opposingly, response times were impaired if the precue and stimulus contradicted each other (incongruent) (Neumann & Klotz, 1994). Although precueing has been extensively researched in mainstream psychology; the transition of research into a sporting domain may improve the understanding of response inhibition in athletes (Farrow & Abernethy, 2002).

Despite the advances of knowledge of EF in athletes, there is another noteworthy limitation. Previous methodologies have used a relatively high variation of participants' age distribution within each group. For example, Vestberg et al. (2017) grouped players age ranging from 12-19 years together, and it has not yet been investigated whether more specific age-group (i.e. stratified by distinctive birth years) differences are revealed in a homogenous population of high-level athletes. From research sourced from a cognitive science domain, EF are still developing rapidly during the adolescent phase (Li et al., 2004). In course of normal aging, early adolescents experience an increased effectiveness to engage in deliberate, goal-orientated thought and action, and these changes are have been reported to be significantly improved between children (mean age = 8 years old) and young adults (mean age = 22.3) (Zelazo et al., 2004), yet more specific age groups are not provided. Furthermore, the enhanced ability to differentiate between goal appropriate responses and goal inappropriate responses that must be suppressed also continues to improve throughout the adolescent phase (Luna, 2009), reflected by reduced reaction times on measures of response inhibition. Accordingly, these studies provide support towards not grouping players with differently developed EF coupled with various levels of domain-specific experience. Contrastingly, identifying specific age group reference values may provide more of a justification of which age groups share similar or distinctive EF to be combined in future studies if required.

Therefore, the aims of this study were threefold. First, to investigate age-group differences on EF tests in a homogenous population of talented youth football players. It is hypothesised that performance on EF tests will be greater in the older groups, as more domain specific experience is expected to transfer into better EF performance. The second aim was to examine the influence of an implicit precue on response times in a precued response time task (PCRTT) as measuring implicit response processes compared to explicit measures may be more appropriate to sports where fast and accurate responses are required. It is further hypothesised that the increase in domain specific experience will also transfer into older players to act on correct information whilst also negate unimportant information, demonstrated by faster reaction times on the PCRTT. The third aim was to develop an overall EF sum score, allowing practitioners to more easily interpret and convey the results of tests to coaches and players alike.

8.1.3 Material and methods

8.1.3.1 Participants.

Seventy-four youth male football players (means ± SD; Age; years of experience playing football = Exp) from four age groups: U12 (n = 15; Age = 10.3 ± 0.6; Exp = 6.4 ± 1.7), U13 (n = 17; Age = 11.2 ± 0.5; Exp = 7.6 ± 1.7), U17 (n = 21; Age = 15.2 ± 0.3; Exp: 11.6 ± 2.5) and U19 (n = 21; Age = 16.7 ± 0.5; Exp = 12.9 ± 2.2) representing a youth academy of an elite German Bundesliga club participated in this study. Prior to commencement of this study, informed consent for all players was received, and the Institutional Ethics Committee approved this study.

8.1.3.2 Procedures and apparatus.

Players conducted a battery of cognitive function tests. Each group was assessed on a separate day in the same week during pre-season. Each player was assigned to a cognitive assessment and rotated to the next free assessment. One staff member remained at each assessment station to give standardized instructions and monitor each player's performance. Each assessment had a standardized familiarisation protocol prior to commencing the experimental trials.

8.1.3.2.1 Vienna Test System: Determination Test

The determination test (Schufried GmbH, Austria) is a complex multi-stimuli reaction test involving the combination of five different coloured stimuli and two acoustic signals (2000 Hz high and 100 Hz low tone) for finger pressing, and two pedal stimuli for the feet. These stimuli corresponded to the pressing of appropriate buttons on the response panel and foot pedals. The determination test aims to measure reactive stress tolerance and the associated reaction speed. The participant must remain composed whilst the quick succession of the single pairing of stimuli and response lasting four minutes. 'Correct responses' describes the total number of accurate responses within the four minutes, and 'response time' is the median response time (s) from the appearance of a stimulus to pressing of the correct button.

8.1.3.2.2 Vienna Test System: Response Inhibition Test

The response inhibition test (Schufried GmbH, Austria) uses a stop signal paradigm. In each trial, the player is presented with an arrow either pointing left or right, to which he must respond by pressing the corresponding button. Each arrow is displayed for one second, and the time before the subsequent arrow appears is also one second. Seventy-six stimuli are ‘go trials’, with the other 24 stimuli having a tone at a pitch of 1000Hz for 100 ms (stop signal). The player must then suppress the already initiated response, known as ‘stop trials’. The time between the presentation of the stimulus and the tone is dependent on the player’s performance, being that if the player responds correctly to a stop signal trial, the interval for the next stop stimuli will occur 50 ms later, and vice versa. Therefore, the correct response to the stimuli will continually progress in difficulty (minimum 50 ms; maximum 350 ms). The dependent variable that reflects the latency of the inhibitory process is stop signal reaction time (SSRT). The SSRT is calculated by deducting the mean stop signal delay from the mean reaction time (s).

8.1.3.2.3 Helix

The Helix (SAP, Walldorf, Germany) is a multiple object tracking assessment in which participants are asked to track multiple players at once. The player stands facing a 180o curved screen (7 m width x 2.16 m height) and must track four out of eight players. Simulated players run around a football field for eight seconds in a randomized fashion and return to back to the start line up. Players must then choose the four players they had to track. Players had four practice trials, and ten marked trials. The maximum score is 40.

8.1.3.2.4 Precued Choice Response Time Task

Participants were required to press the button on a joystick panel associated with a stimulus circle presented on the laptop screen as fast and accurate as possible. The PCRTT developed using Unity software (Unity, Version 5.4.0f3, 2016). Four blank stimulus circles were presented in a horizontal line, with one circle turning yellow in colour after a randomised (2-4 second) fore-period length. Each circle each had a diameter of 512 pixels and an edge width of 5 pixels on a 13.2-inch display. Prior to the appearance of the stimulus, a three second countdown timer was shown. After the appearance of the four stimulus circles, a small dot was appeared for 43 ms in the centre of one stimulus circle, 86 ms prior to the circle turned yellow. The duration of the precue was based on prior research supporting that precue duration below the 100 ms threshold are suitable to be used as unconscious precues (Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003), and a 43 ms precue has been identified as an appropriate precue length in research involving cognitive responses (Dehaene et al., 1998).

Twenty-four trials were conducted. Twelve trials had the small dot appear in the same circle as the yellow dot (congruent) and the other twelve trials had the dot appear in a different circle as the yellow dot (incongruent). Response time (given in ms) was measured as the duration between the appearance of the stimulus circle (turned yellow) on the computer screen and the moment the button was pressed by the participant. A visual depiction of the task used can be found in Figure 12.

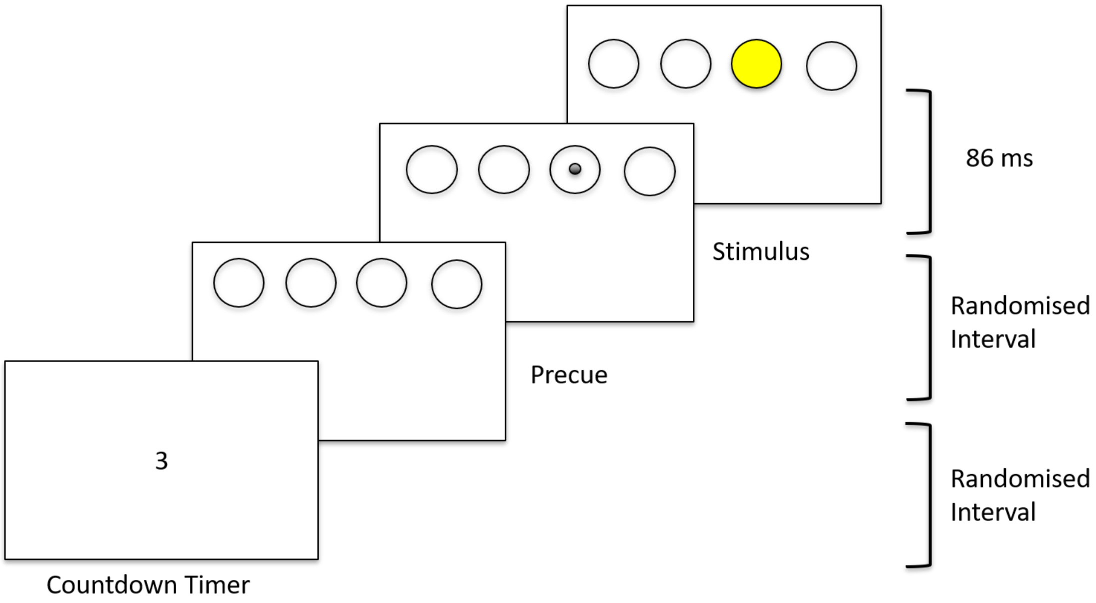


Figure 12. Depiction of the Precued Choice Response Time Task.

8.1.4 Statistical analysis.

Following data collection, participant responses were initially analysed according to their accuracy. Responses that did not correspond with the stimulus circle (i.e. when a false response was given) were considered incorrect and the response time of the respective trial was discarded due to the low frequency of incorrect responses (n = 53). Furthermore, to highlight instances in which the participants missed the controller button or did not press it sufficiently, an outlier labelling rule was used following the methods outlined by Hoaglin et al. (1986), and applied on an individual basis to limit within subject variance. Furthermore, the interquartile range was multiplied by 1.5, and trials with response times beyond the 25th and 75th percentiles ± the inter-quartile range were considered outliers and therefore discarded (n = 108). The remaining raw responses (n = 1615) from this test were grouped according to 'condition' (i.e. congruent or incongruent trials), and the mean of the correct responses from each participant in each condition was computed.

Normalized values were calculated from z-scores for all items as per: Normalized score = 100+(Z-score*15). When larger numbers represented poorer scores, the z-scores were inversed before normalization, so a higher value was associated with a better score. These normalized values were then used in two factor analyses to develop a total executive function sum score (EF sum score) for all players. An exploratory factor analysis used principal component analysis with a varimax rotation to determine the number of factors revealed within all EF assessments to assess the feasibility of one overarching EF factor, a second confirmatory factor analysis then investigated item loadings when all items were forced to load onto a single factor. Items were discarded when they were deemed to be 'unimportant', i. e. when their communality was found to be lower than 0.40. From the final factor analysis, a new EF variable was developed using each individual item's factor loading as a weighting system.

Finally, (i) one Repeated Measures Analysis of Variance, (ii) two Multivariate Analyses of Variance (MANOVA) and (iii) two one-way Analysis of Variance (ANOVA) were used to investigate age-group differences in: (i) PCRTT response time where congruent-incongruent scenarios were included as a within-subjects variable, (ii) Determination Test performance with response time and correct responses entered as dependent variables and Vienna Test performance with start-stop response time and response time as dependent variables, and (iii) Helix performance score and the newly developed EF sum score. Bonferroni corrections were used to investigate multiple comparisons between age groups and partial eta squared effect sizes were used throughout to investigate the magnitude of any observed effects using Cohen (1988) guidelines for interpreting effect sizes: 0.01-

0.06 = small effect, 0.06-0.14 = moderate effect and >0.14 = large effect. In all analyses, partial eta squared effect sizes were calculated and the significance level was set at $p < 0.05$. All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 24.

8.1.5 Results

The descriptive statistics and results of (M)ANOVAs for the EF tests can be found in Table 11.

Table 11. Means ± standard deviations (95% confidence intervals), and results of (M)ANOVAs for the executive function tests.

Test	Variable	U12 (n = 15)	U13 (n = 17)	U17 (n = 21)	U19 (n = 21)
PCRTT	Congruent RT (ms)	0.590±0.059 (0.562-0.619)	0.578±0.065 (0.554-0.603)	0.547±0.047 (0.523-0.571)	0.537±0.053 (0.512-0.561)
	Incongruent RT (ms)	0.612±0.056 (0.582-0.641)	0.607±0.069 (0.582-0.632)	0.569±0.052 (0.544-0.594)	0.558±0.049 (0.533-0.582)
Determination Test	Correct Answers (n)	215.07±25.04 (201.20-228.93)	238.78±32.477 (222.63-254.93)	263.90±29.64 (250.41-277.40)	291.14±41.220 (272.38-309.91)
	RT (ms)	0.835±0.066 (0.798-0.871)	0.758±0.096 (0.710-0.805)	0.651±0.055 0.626-0.677)	0.619±0.065 (0.589-0.648)
Response Inhibition Test	SSRT (ms)	0.239±0.101 (0.183-0.295)	0.204±0.696 (0.174-0.237)	0.134±0.054 (0.109-0.158)	0.117±0.045 (0.097-0.138)
	RT (ms)	0.547±0.064 (0.511-0.582)	0.503±0.100 (0.456-0.550)	0.446±0.074 (0.412-0.479)	0.422±0.046 (0.402-0.443)
Helix	Helix (% correct)	76.00±7.12 (72.07-79.94)	75.24±7.82 (71.68-78.80)	81.79±8.07 (78.11-85.46)	81.79±8.30 (78.01-85.56)
Total	EF Sum Score (AU)	406.71±36.42 (387.41-426.02)	437.58±49.74 (419.45-455.72)	485.87±31.77 (469.55-502.19)	506.44±53.29 (490.12-522.75)

Note: AU= Arbitrary Unit; PCRTT = Precued Choice Response Time Task; EF = Executive Functions; RT = Response Time; and SSRT = Stop Signal Response Time; ES = partial eta squared effect sizes. * = $p < 0.05$; ** = $p < 0.001$

8.1.5.1 Vienna Test System: Determination Test

Results from a MANOVA revealed a multivariate effect of age group on the Determination Test (F(6,140)=11.670, p<0.001, ES=0.38). Further univariate analysis revealed a significant age group effect for number of correct responses (F(3,71)=17.453, p=<0.001, ES=0.42) and response time (F(3,71)=33.942, p=<0.001, ES=0.59). Post-hoc analyses demonstrated that the U12 age group had a significantly lower number of correct responses than the U17 (p=<0.001) and U19 (p=<0.001) age groups, while the U13 had poorer scores than the U19 group (p=<0.001). Additionally, the U12 group's response time was significantly slower than the U13 (p=0.018), U17 (p=<0.001) and U19 (p=<0.001), and the U13 group's response times were significantly slower than the U17 (p=<0.001) and U19 (p=<0.001) group.

8.1.5.2 Vienna Test System: Response Inhibition Test

A MANOVA revealed a significant multivariate effect of age group on Vienna Test System Response Inhibition Test (F(6,144)=6.142, p<0.001, ES=0.20). Subsequent univariate analysis demonstrated a significant effect of age group on SSRT (F(3,73)=13.172, p=< 0.001, ES=0.35) and response time (F(3,73)=10.338, p=<0.001, ES=0.30). Post-hoc analyses demonstrated that the SSRTs were significantly slower in both the younger groups compared to the older groups. More specifically, the U12 group was slower compared to the U17 (p=<0.001) and the U19 (p=<0.001) groups, while the U13 group was also slower than the U17 (p=0.005) and U19 (p=<0.001) groups. Furthermore, response times were significantly slower in the U12 group than in the U17 (p=0.001) and U19 (p=<0.001) group, and also the U13 group was slower compared to the U19 (p=0.005) group.

8.1.5.3 Precued Choice Response Time Task

The repeated measures ANOVA did not reveal a significant interaction effect of congruency*age group (F(3,74)=0.33, p=0.80, ES=0.01). However, this analysis did reveal a significant within-subjects effect of congruency (F(1,74)=51.32, p<0.001, ES=0.41) and a significant between-subjects effect of group (F(3,74)=4.30, p=0.008, ES=0.15). Post-hoc analyses demonstrated that overall, responses in congruent trials were faster than in incongruent trials. More specifically, U12 players had significantly poorer overall response times than U19 players in both congruent (p=0.04) and incongruent (p=0.018) trials.

8.1.5.4 Helix

A one-way ANOVA revealed a significant age group effect for response accuracy in the Helix (F(3,74)=4.05, p=0.01, ES=0.14). A trend towards lower response accuracy was observed in the U13 group compared to the U17 (p=0.053) and U19 (p=0.053) groups, but this failed to reach statistical significance.

8.1.5.5 Executive function sum score

Based on the confirmatory factor analysis, the following coefficients were derived and were used to calculate an EF sum score that explains 60% of the variance in the derived factor:

EF sum score = (0.720∗Response Time Congruent Inverse) + (0.699∗Response Time Incongruent Inverse) + (0.756∗Determination Test Number of Correct Answers) + (0.828∗Determination Test Response Time Inverse) + (0.853∗SSRT Inverse) + (0.766∗Response Inhibition Time Inverse).

The ANOVA revealed an effect of age group on ExF score (F(3,70)=25.82, p=<0.001, ES=0.53). More specifically, U17 and U19 players had better EF than U12 and U13 players (Table 11 and Figure 13).

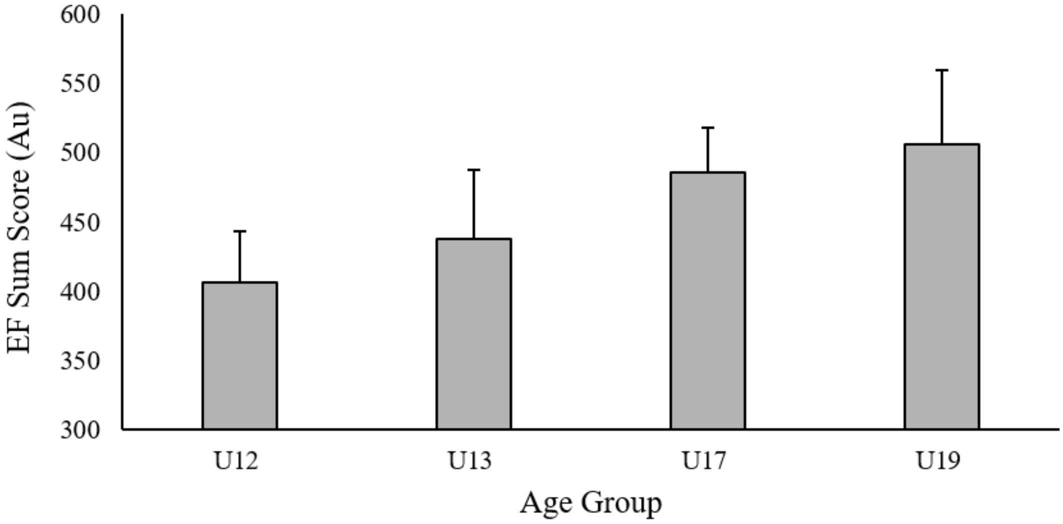


Figure 13. An example of the simplified executive function sum score.

8.1.6 Discussion

This study used a battery of non-sport specific cognitive function tests within an elite level club's academy to investigate age-group differences on performance. The results from this study supported the hypothesis that older football players performed significantly better on EF tests compared to their younger counterparts in a highly talented population. In fact, significant group by performance interaction effects were observed for each test. Additionally, to the authors' knowledge, the present study is the first to demonstrate that implicit stimuli can either enhance or hinder motor behaviour in highly talented youth football players based off the congruency of the delivered precue.

In combination, the implicit and explicit response inhibition tests exhibited similar pattern; significant age group effects coupled with large effect sizes indicate a refinement of existing response inhibition ability with increases in age and playing experience. Distinctly, the explicit stop-signal response inhibition test revealed that not only were the younger groups (U12-13) both significantly slower compared to each of the older groups (U17- U19), but also were significantly different between each other. These findings are aligned with previous non-sport specific research stating that the ability to plan and prepare a response are apparent in early adolescence, and that during the adolescent phase is where an improved ability to more consistently filter out irrelevant responses that are not aligned with the desired task goal occurs (Luna, 2009). Future research should investigate whether the magnitude of change between additional age groups that were not included in this study are as prominent during the adolescent phase.

Furthermore, the PCRTT results revealed that during congruent trials, the U12 group was significantly slower than the U19 group; while in the incongruent trials, both younger (U12-13) groups were significantly slower than the U19 group. Collectively these results imply that athletes undergoing development throughout adolescence coupled with gaining more game-specific experience in rapid decision-making scenarios translates to a more refined ability to (i) use congruent precues to their advantage, and (ii) consistently negate unimportant information from incongruent precues than players with less experience. These findings could have important implications for sport coaching. For example, training a player’s ability to consistently not act on irrelevant cues throughout the duration of the match has important implications for decision-making in sport. There is a myriad of examples in sport where unimportant information surrounds athletes. For example, players attempting to provide the opponent with false information to gain an advantage (i.e. a pass-fake in a team sport), or visual and auditory distractions from the crowd during a basketball free throw.

The results from the Helix were not clear enough to entirely support previous research that has reported a clear distinction between the level of athletic performance and corresponding fundamental mental capacities for learning an abstract and demanding dynamic scene (Faubert, 2013a). However, Faubert (2013a) noted that rapid learning in complex and unpredictable dynamic contexts is one of the critical components required for elite performance. Therefore, the results from the current study imply that the necessary threshold for multiple object tracking performance can already be established from the amount of experience a U12 player has in high-level football (i.e. around 6 years in this case). Supporting research reported that superior perceptual-cognitive skills in elite football players compared to sub-elite player were already apparent at the age of nine (Ward & Williams, 2003). Although, it remains difficult to determine if the elite youth players demonstrate these superior cognitive abilities because of a natural born advantage (i.e. nature) or the amount of high-quality years of playing experience received prior to the assessments (i.e. nurture) (Scharfen & Memmert, 2019).

The last aim of the study was to overcome the challenge that academics and practitioners face with creating a strategy to more easily convey the results of these cognitive tests for both coaches and players. Overcoming the translation/adoption failure (i.e. where the information is not understood by the intended audience (Eisenmann, 2017)) can be difficult as measuring EF requires multiple tests with various interpretations of the results. Although the equation provided within the current study is unique to the battery of tests that were used, it demonstrated that a sum score can be used to differentiate between age groups (see Figure 14). Therefore, academics and practitioners could create their own unique sum score to allow for a smoother translation between the relevant results sourced from the data to the intended audience (Buchheit, 2017). From a practical perspective, an all-encompassing sum score could provide practitioners with age-group reference values from which players' performance scores could either be compared against other teammates or their own previous test results. This value can also be provided to coaches or players as an easy-to-interpret summary of each individual player or group EF performance, with the ability to provide further information of each test performance if required.

Although this study presents important findings for researchers and practitioners alike, several limitations should be acknowledged. First, this study stratified players only by their respective age groups. Thus, a more in-depth analysis of the potential independent effects such as field position, more detailed playing experience forms and the inclusion of more age groups are needed to form a focus of future research on the role of EF in football. Second, despite the validity and reliability of the Vienna Test System being previously confirmed by a variety of studies (Ljac et al., 2012; Schuhfried, 2001; Whiteside et al., 2003), Baláková et al. (2015) called for further investigation of the reliability and validity, stating that the vague design of the test in addition to laboratory conditions is not suitable to predict talent in young football players.

8.1.7 Conclusion

The current study added to this growing body of research by testing the EF of distinct multiple age-groups within a high-level academy. Overall, older athletes with more experience playing football had better EF than younger athletes. Furthermore, noticeable improvements in EF performance can also be observed with an increase of one year in age and playing experience during early adolescence. Thus, future studies should take caution when grouping players together with multiple birth years, especially in younger populations where the magnitude of change between ages are more prominent. Lastly, the PCRTT could be used as an additional measure within an EF battery. Choice reaction time tasks are common in to assess reaction times, but only using explicit information. Therefore, the results from this implicit test could further our understanding of how athletes are able to act upon both implicit and explicit sources of visual information and in the future should be compared with additional populations.

8.2 Opinion Piece: Taking the First Steps Towards Integrating Testing and Training Cognitive Abilities Within High-Performance Athletes; Insights from a Professional German Football Club.

An opinion piece was written together with the practitioners of the club in order to discuss the implementation of domain-generic assessments in a sporting environment.

This opinion piece has been accepted for publication. The full reference of the manuscript is:

Beavan, A., Spielmann, J., & Mayer, J. (2019). Taking the First Steps Towards Integrating Testing and Training Cognitive Abilities Within High-Performance Athletes; Insights from a Professional German Football Club. *Frontiers in Psychology*, *10*, 2773.

8.2.1 Abstract

Every elite athlete has a unique combination of physical, technical and cognitive attributes that together, allow them to compete at the highest level of their respective sport. Understanding the complex relationship of these elements requires scientists and practitioners alike to constantly explore new performance-based assessment tasks. In recent years, the addition of assessing the cognitive abilities of athletes, known as Executive Functions (EFs) has become a fruitful new area of research and has also gained popularity in the applied field. Collectively, the recent studies focusing on measuring EFs have documented differences in EF performance between elite and non-elite athletes consistently through junior to adult populations, providing a substantial basis that advocates the use of EF testing as a prognostic tool for talent identification in sport. However, there are many limitations that remain in this area of research and should be considered when incorporating EF testing into an assessment battery. Therefore, this opinion piece seeks to discuss the issues relating to measuring EFs within a sports team and propose practical guidelines that will allow both researchers and practitioners alike to effectively address these limitations, and further our understanding of the role that EFs play in athletic settings. Furthermore, with the intention of demonstrating practical applications of the research within an applied field, this opinion piece is complimented by a case study from a professional German Bundesliga club that has employed EF testing for more than five years. The case study provides insights into how every player from the junior to professional squads have a cognitive profile, and the process of how this profile is measured through a testing battery and trained using cognitive tasks relating to the "broad transfer" hypothesis. Finally, details are provided into how this club uses player cognitive profiles as an additional monitoring tool for their athletes throughout the competitive season, and how age-grouped norms play a role within their talent identification process.

Keywords: Executive Functions; Game Intelligence, Computer Testing, Soccer, Talent Identification

8.2.2 Introduction to executive functions

Executive functions (EFs) are higher-level cognitive functions which refer to the family of top-down mental processes that sub serve goal-directed behaviour (Miller & Cohen, 2001), and are relevant in situations that require a fast and flexible adjustment of behaviour to the changing demands of the environment (Zelazo et al., 2003). There is a general agreement that the three core EFs are: inhibition, working memory and cognitive flexibility (Diamond, 2013). Previous research has proposed that EFs play an essential role in sport, connecting successful athletes with greater cognitive abilities (Jacobson & Matthaeus, 2014). Therefore, academics and practitioners alike are implementing EF testing batteries as an additional measure of performance. During the planning and implementation of EF assessments, there are obstacles that may be encountered by practitioners and coaches throughout all levels of play (i.e. amateur to professional leagues), such as the choice of assessments, the financial and opportunity costs, how to convey the data into meaningful results to the team, and what assumptions can currently be made from the data that is supported by research. By using the experience that we have gained by testing and training EFs for over five years at a professional 1st division football (Association Football) club in Germany, we aim to share our opinion on how to tackle these issues. We also aim to discuss the remaining barriers in EF research in hope of having more researchers and practitioners working together to collectively overcome them.

8.2.3 Setting up a protocol

The choice of assessments is the foundation that all future assumptions are based upon, and it is recommended to have a test measuring each EF independently. However, a large hurdle that clubs will inevitably encounter is the financial cost of implementing new assessment tasks. Despite some companies marketing their cognitive testing for upwards of $30,000 (i.e. CANTAB), this does not mean that cognitive batteries should only be implemented by the teams with larger budgets. Assessments such as the Design Fluency task to assess cognitive flexibility, and the Digit Symbol Substitution task to assess working memory can both be completed by pen and paper, whereas the N-back task to assess working memory and the Stroop Task to assess response inhibition can be created using PowerPoint. Furthermore, establishing mutualistic relationships with universities can provide opportunities for teams to either use the psychological tools owned by the university in exchange of participants' data for research purposes, and/or to help develop their own EF assessments.

8.2.4 Data collection

Our club assesses every players' EFs once during the pre-season and once halfway through the season. We further recommend collecting contextual information about each player such as: birthdate, birth quartile and birthplace, intelligence quotient (IQ) or a similar academic grading score, history questionnaires on their years of experience playing both their main sport and any additional sports participation, and hours of training per week both in structured and unstructured playing environments (Mann, Dehghansai, & Baker, 2017). Contextual information can help improve our understanding of whether high-level athletes display better EFs than their lower-level and non-athletic counterparts because they were either born with greater cognitive abilities (i.e. nature), or whether their higher cognitive abilities are sport/environmentally-induced (i.e. nurture) (Scharfen & Memmert, 2019).

8.2.5 Communicating the results

Measuring EFs requires multiple complex assessments in a psychological domain and ensuring that the results are understood by the intended audience can be difficult (Eisenmann, 2017). Some strategies have been recommended in the literature. For example, Sakamoto et al. (2018) created a composite score by changing the results of each individual test into a z-score and then adding the z-scores together. In a practical sense, the idea of creating a single number that encompasses different scales for each variable can make the results easier to interpret and can be relatively easy to implement. However, caution should be taken in this approach as it may under-power the changes for each test. A more complex method that this club developed is an ‘EF sum score’, which combines all results into one total value (Beavan et al., 2019). Figure 14 displays the practicality of the sum score to provide a smoother translation of the relevant results to the intended audience (Buchheit, 2017).

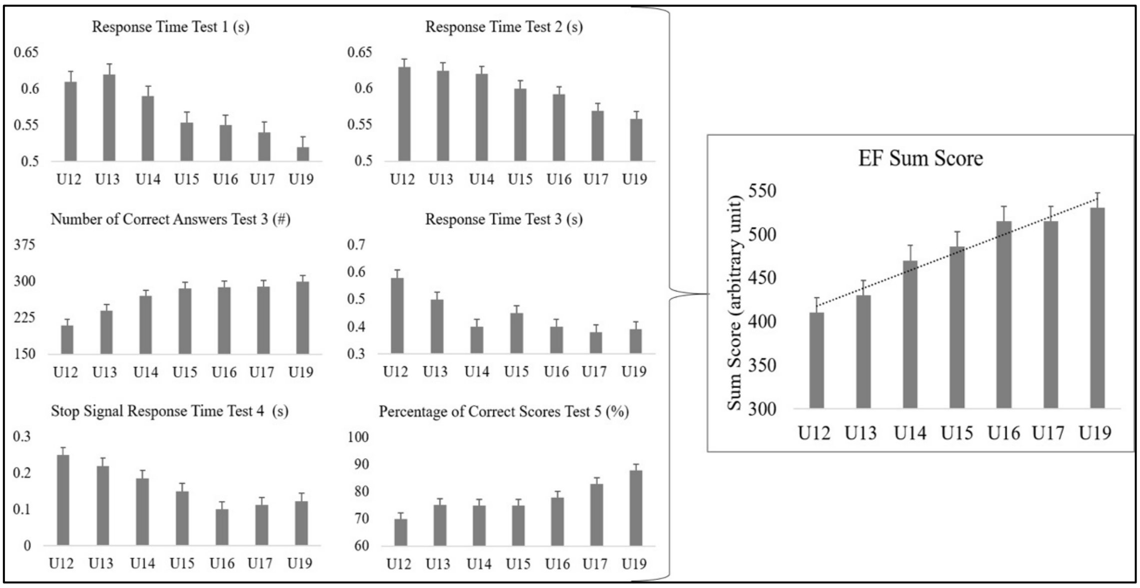


Figure 14. Mock data demonstrating how the results from individual assessments with various units can be combined in one summary graph. Values were normalized and then used in a two factor analyses to develop a total executive function sum score (EF sum score) for all players. A new EF variable was developed using each individual item’s factor loading as a weighting system, so each change in one unit of performance was equal across each assessment. Our equation unique to our assessments (and serves only as an example) are: EF sum score = (0.720∗Response Time Congruent Inverse) + (0.699∗Response Time Incongruent Inverse) + (0.756∗Determination Test Number of

Correct Answers) + (0.828∗Determination Test Response Time Inverse) + (0.853∗SSRT Inverse) + (0.766∗Response Inhibition Time Inverse).

8.2.6 What inferences can currently be made from executive function results?

We evaluate our players' EF performance relative to their age group norms. However, there is a high variation between players on EFs across each age group, and this has similarly been reported in another study (Sakamoto et al., 2018). Our practitioners report that players who are the true elite academy players that yield the potential to make it to the adult professional level are also the players who are outperforming their age-group in the EF assessments, and the variation is caused by the many athletes that do not yet hold this 'elite' status amongst coaches. Longitudinal data is needed in order to support this standpoint, but an interesting next step is to relate EFs to a panel of coaches' ratings of skill and potential of each player to reach the professional level rather than their age. Furthermore, various levels of motivation may influence the attainment of scores across the battery, specifically in EF assessments where athletes may be disinterested in performing non-sport specific testing. Although this remains difficult to account for, the underlying principle is that practitioners should consider the subjective contextual variables when interpreting their team's EF results. Variables such as the presence of a coach, motivation, players' contract situations, wellness, and whether the participants understand why they are doing the assessments all may influence the test results (Stiroh, 2007); but these variables have remained difficult to account for objectively in scientific research that may help explain the observed variance.

Despite these obstacles, a recent meta-analysis reported that a positive finding exists regarding the importance of EFs in football (Scharfen & Memmert, 2019). Higher-level athletes demonstrated better EFs than lower level athletes, and it has therefore been advocated that EF testing could play a role within the talent identification process (Huijgen et al., 2015; Montuori et al., 2019; Sakamoto et al., 2018). Yet additional research outside of football did not confirm the generalization of better EFs linked with expertise, where no differences between different levels of expertise in tennis (Kida et al., 2005), ice hockey (Lundgren et al., 2016), or basketball (Nakamoto & Mori, 2008) were reported. Therefore, there is a lack of agreement in the literature on whether EFs as a prognostic tool for football talent has practical validity. Albeit, previous research has attempted to understand if EFs could help identify talent. For example, Sakamoto et al. (2018) reported that players who were accepted into an academy exhibited better EFs than players who were rejected. Yet we need to assess whether these statistically significant differences are also practically relevant. The between-group difference on a Stroop task was on average +3 correct answers out of 100 (rejected group: 31.3 ± 9.6; approved group: 34.5 ± 8.6; p=0.001; effect size =0.35). In other words, the groups that were accepted and not accepted into the academy overlapped by about 86% (Magnusson, 2014). Although the differences reached statistical significance, whether they are large enough to help a coach distinguish between a player that should be accepted or rejected from an academy remains questionable.

To date, longitudinal studies in athletic populations are lacking, leaving only weak generalizations of the EF developmental trajectories from existing longitudinal studies in general populations. Therefore, longitudinal research is needed to understand if assessments of EFs are able to help practitioners predict talent in young athletes. For example, does assessing EFs have more value to help in the detection of potential talent from a heterogenous cohort that does not yet compete at a high-level (i.e. a large group of school kids), or in the identification of the best performers within a homogenous cohort of already competing athletes (i.e. high-level academy players likely to become adult-professionals)? Currently, no study has yet to demonstrate that athletes with higher EF scores become more successful in their sport.

8.2.7 Cognitive training

The cognitive training approach stems from the “broad training hypothesis” which states that training basic cognitive skills could improve EFs and would therefore translate into better performances when utilizing EFs (Walton, Keegan, Martin, & Hallock, 2018). For example, 10 sessions of cognitive training in a laboratory improved football players’ on field passing decision-making accuracy by 15% (Romeas, Guldner, & Faubert, 2016), and Ducrocq, Wilson, Vine, and Derakshan (2016) reported the possibility to enhance sporting performance by improving the inhibitory control of tennis athletes. Importantly, there remains a large debate on whether training with computer-based cognitive tasks can broadly transfer into real-world performances. An extensive review by Simons et al. (2016) conveyed that no compelling evidence currently exists showing a true positive transfer of cognitive training interventions to real-world tasks. Recently, Harris et al. (2018) mentioned that although the lack of evidence across the literature is not an encouraging sign that it would work for athletes, only one study directly examined the benefits of a cognitive training program on sporting transfer task. Seemingly, if academics and practitioners are wanting to overcome this paucity of knowledge directly in sport, they are recommended to read Walton et al. (2018) who provides recommendations of how to best explore the link between cognitive and sporting abilities.

It is important that if clubs decide to invest in training EFs, the staff should further discuss both the financial cost of purchasing the equipment and the opportunity cost of spending the time and money on a different task (Simons et al., 2016). In order to reduce the opportunity cost, we emphasize the importance of cognitive training towards players who are: i) regressing from their previous EF scores, ii) wanting to engage in cognitive training, iii) injured, and iv) scoring in the lowest third within their age norms. The reason behind training players who performed in the lowest third is based on previous non-sporting literature reporting that a threshold effect may exist with natural abilities and expertise, where any improved ability beyond the requirement to compete at a high-level (i.e. the threshold) may not further improve performance (Terman & Oden, 1959). Contrastingly, this also means that players who are under the threshold may yield the potential to enhance their performance by improving their EFs (Diamond, 2016). Diamond (2016) advocated that training EFs are important to the future success of individuals and should begin as young as possible; especially in individuals that yield the lowest scores to ensure that their deficiencies are not enlarged over the coming years. Although the threshold hypothesis is still relatively new when explaining the role of EFs in sport, it has been used to explain differential correlations between intelligence (i.e. IQ), creativity (Jauk et al., 2013), and future career achievement (Baird, 1985; Gagné, 2004; Terman & Oden, 1959).

8.2.8 Conclusion

Practitioners are commonly the first to apply and test new methods with science following in attempt to examine their practices. The measurement and training of cognitive abilities such as EFs are becoming a popular new approach in sporting clubs. However, with EF research being a relatively young area of research, the importance of EFs in sport remains widely unknown, and it remains unclear if the measurement and training of EFs are justifiable to help predict future talent. Pending further research, a current focus on EF development in the lower achieving athletes may be a more suitable use. Being well-informed of the scientific literature will help in overcoming the delicate balancing act between administering good scientific practice methodology and what is functional for the club with respect to the aforementioned hurdles of implementing the testing and training of EFs. Therefore, new research-practitioner relationships are a cornerstone to furthering our understanding of the role that EFs play in sport. Collectively, a promising opportunity exists to help overcome the limitations in the literature if research informed protocols are put in place with a purpose of improving the support towards the testing and training EFs.

8.3 Ethical approval

Translated from German to English using DeepL software:

“The Ethics Committee of the Faculty of Empirical Humanities and Economics at the University of Saarland has examined your application 18-06 "Collection and Training of Executive Functions" and decided to approve it without stipulation.”

UNIVERSITÄT
DES
SAARLANDES

Universität des Saarlandes | Der Vorsitzende der Ethikkommission der Fakultät für Empirische Humanwissenschaften und Wirtschaftswissenschaft | Prof. Dr. Cornelius König | Postfach 15 11 50 | D-66041 Saarbrücken

Prof. Dr. Jan Mayer
Sportwissenschaft Geb. 8.2
Universität des Saarlandes
66123 Saarbrücken

Universität des Saarlandes
Fakultät für Empirische
Humanwissenschaften und
Wirtschaftswissenschaft

Der Vorsitzende der
Ethikkommission
Prof. Dr. Cornelius König

Postfach 15 11 50
D-66041 Saarbrücken

T: +49 (0) 681 302 3629
F: +49 (0) 681 302 3628
ckoenig@mx.uni-saarland.de
www.uni-saarland.de/ao

Datum 26.02.2018
Betreff Ethik-Antrag

Sehr geehrter Herr Prof. Mayer,

die Ethikkommission der Fakultät für Empirische Humanwissenschaften und Wirtschaftswissenschaft der Universität des Saarlandes hat Ihren Antrag 18-06 „Erfassung und Training von Exekutivfunktionen“ begutachtet und entschieden, ihn ohne Auflage zu genehmigen.

Freundliche Grüße,

Cornelius König

8.4 Statement of the Contribution of Authors

I hereby declare that my contribution to each of the published or in press manuscripts within this thesis, as outlined on the next page, to be accurate and true.

Adam Beavan
Signature: Date:01/04/2020

Job Fransen
Signature: Date:03/04/2020

Jan Spielmann
Signature: J.Spielmann Date: 01/04/2020

Jan Mayer
Signature: Date:06/04/2020

Sabrina Skorski
Signature: Date:08/04/2020

Tim Meyer
Signature: Date: 13/04/2020

Vincent Chin
Signature: Vincent Date:16/04/2020

Louise M. Ryan
Signature: Date:14/04/2020

Lars Hanke
Signature: Date: 03/04/2020

Study 1: Age-Related Differences in Executive Functions Within High-Level Youth Soccer Players.

Author	**Tasks**	**Contribution % Overall**
Adam Beavan	Study conception & design Acquisition of data Analysis and interpretation of data Drafting of manuscript Critical revisions	55%
Jan Spielmann	Study conception & design Acquisition of data Critical revisions	10%
Jan Mayer	Study conception & design Critical revisions Supervision	5%
Sabrina Skorski	Study conception & design Critical revisions Supervision	5%
Tim Meyer	Study conception & design Critical revisions Supervision	5%
Job Fransen	Study conception & design Analysis and interpretation of data Drafting of manuscript Critical revisions Supervision	20%

Study 2: The Rise and Fall of Executive Functions in High-Level Football Players.

Author	**Tasks**	**Contribution % Overall**
Adam Beavan	Study conception & design Acquisition of data Analysis and interpretation of data Drafting of manuscript Critical revisions	55%
Jan Spielmann	Study conception & design Acquisition of data Critical revisions	10%
Jan Mayer	Study conception & design Critical revisions Supervision	5%
Sabrina Skorski	Study conception & design Critical revisions Supervision	5%
Tim Meyer	Study conception & design Critical revisions	5%

	Supervision	
Job Fransen	Study conception & design Analysis and interpretation of data Drafting of manuscript Critical revisions Supervision	20%

Study 3: The Footbonaut as a new football-specific skills test: reproducibility and age-related differences in highly trained youth players.

Author	**Tasks**	**Contribution % Overall**
Adam Beavan	Study conception & design Acquisition of data Analysis and interpretation of data Drafting of manuscript Critical revisions	55%
Jan Spielmann	Study conception & design Acquisition of data Critical revisions	10%
Jan Mayer	Study conception & design Critical revisions Supervision	5%
Sabrina Skorski	Study conception & design Critical revisions Supervision	5%
Tim Meyer	Study conception & design Critical revisions Supervision	5%
Job Fransen	Study conception & design Analysis and interpretation of data Drafting of manuscript Critical revisions Supervision	20%

Study 4 : A longitudinal analysis of the executive functions in high-level football players.

Author	**Tasks**	**Contribution % Overall**
Adam Beavan	Study conception & design Acquisition of data Analysis and interpretation of data Drafting of manuscript Critical revisions	50%
Vincent Chin	Analysis and interpretation of data Drafting of manuscript Critical revisions	10%
Louise M. Ryan	Analysis and interpretation of data Drafting of manuscript Critical revisions	5%

Jan Spielmann	Study conception & design Acquisition of data Critical revisions	5%
Jan Mayer	Study conception & design Critical revisions Supervision	5%
Sabrina Skorski	Study conception & design Critical revisions Supervision	5%
Tim Meyer	Study conception & design Critical revisions Supervision	5%
Job Fransen	Study conception & design Analysis and interpretation of data Drafting of manuscript Critical revisions Supervision	15%

Study 5: Using Stroboscopic Vision to Restrict Visual Feedback in a Football Specific Skill Assessment.

Author	**Tasks**	**Contribution % Overall**
Adam Beavan	Study conception & design Acquisition of data Analysis and interpretation of data Drafting of manuscript Critical revisions	55%
Job Fransen	Study conception & design Analysis and interpretation of data Drafting of manuscript Critical revisions Supervision	15%
Lars Hanke	Study conception & design Acquisition of data	10%
Jan Spielmann	Study conception & design Acquisition of data Critical revisions	5%
Sabrina Skorski	Study conception & design Critical revisions Supervision	5%
Jan Mayer	Study conception & design Critical revisions Supervision	5%
Tim Meyer	Study conception & design Critical revisions Supervision	5%

Study 6: Associating visual exploration and football passing performance in elite U13 and U23 Football players.

Author	Tasks	Contribution % Overall
Thomas McGuckian	Study conception & design Analysis and interpretation of data Drafting of manuscript Critical revisions	45%
Adam Beavan	Study conception & design Acquisition of data Analysis and interpretation of data Drafting of manuscript Critical revisions	40%
Jan Mayer	Critical revisions Supervision	5%
Daniel Chalkley	Analysis and interpretation of data Critical revisions	5%
Gert-Jan Pepping	Study conception & design Critical revisions Supervision	5%

Opinion Piece: Taking the First Steps Towards Integrating Testing and Training Cognitive Abilities Within High-Performance Athletes; Insights from a Professional German Football Club.

Author	Tasks	Contribution % Overall
Adam Beavan	Study conception & design Drafting of manuscript Critical revisions	80%
Jan Spielmann	Study conception & design Critical revisions	10%
Jan Mayer	Study conception & design Critical revisions Supervision	10%

Editorial: Extraordinary Tools Require Extraordinary Evidence.

Author	Tasks	Contribution % Overall
Adam Beavan	Drafting of manuscript Critical revisions	100%

8.5 Curriculum Vitae

The curriculum vitae was removed from the electronic version of the doctoral thesis for reasons of data protection.

Chapter 9: Bibliography

Ali. (2011). Measuring soccer skill performance: a review. *Scandinavian journal of medicine & science in sports, 21*(2), 170-183.

Ali, A., Williams, C., Hulse, M., Strudwick, A., Reddin, J., Howarth, L., . . . McGregor, S. (2007). Reliability and validity of two tests of soccer skill. *Journal of Sports Sciences, 25*(13), 1461-1470.

Anderson, P. (2002). Assessment and development of executive function (EF) during childhood. *Child neuropsychology, 8*(2), 71-82. doi:https://doi.org/10.1076/chin.8.2.71.8724

Aquino, R., Marques, R. F. R., Petiot, G. H., Gonçalves, L. G. C., Moraes, C., Santiago, P. R. P., & Puggina, E. F. (2016). Relationship between procedural tactical knowledge and specific motor skills in young soccer players. *Sports, 4*(4), 52.

Araujo, D., Davids, K., & Hristovski, R. (2006). The ecological dynamics of decision making in sport. *Psychology of Sport and Exercise, 7*(6), 653-676.

Ardila, A., & Rosselli, M. (1994). Development of language, memory, and visuospatial abilities in 5-to 12-year-old children using a neuropsychological battery. *Developmental Neuropsychology, 10*(2), 97-120. doi:https://doi.org/10.1080/87565649409540571

Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in cognitive sciences, 4*(11), 417-423.

Baird, L. L. (1985). Do grades and tests predict adult accomplishment? *Research in Higher Education, 23*(1), 3-85. doi:https://doi.org/10.1007/BF00974070

Baker, J., Cote, J., & Abernethy, B. (2003). Sport-specific practice and the development of expert decision-making in team ball sports. *Journal of Applied Sport Psychology, 15*(1), 12-25.

Baláková, V., Boschek, P., & Skalíková, L. (2015). Selected cognitive abilities in elite youth soccer players. *Journal of Human Kinetics, 49*(1), 267-276. doi: https://doi.org/10.1515/hukin-2015-0129

Ballester, R., Huertas, F., Uji, M., & Bennett, S. J. (2017). Stroboscopic vision and sustained attention during coincidence-anticipation. *Scientific Reports, 7*(1), 17898.

Barela, J., Rocha, A., Novak, A., Fransen, J., & Figueiredo, A. (2019). Age differences in the use of implicit visual cues in the decision-making. *Brazilian Journal of Motor Behavior, 13*(2), 86-93. doi:https://doi.org/10.20338/bjmb.v13i2.139

Barnett, S. M., & Ceci, S. J. (2002). When and where do we apply what we learn?: A taxonomy for far transfer. *Psychological Bulletin, 128*(4), 612. doi:https://doi.org/10.1037/0033-2909.128.4.612

Barnsley, R. H., & Thompson, A. H. (1988). Birthdate and success in minor hockey: The key to the NHL. *Canadian Journal of Behavioural Science/Revue Canadienne des Sciences du Comportement, 20*(2), 167.

Beavan, A., & Fransen, J. (2016). The influence of coaching instructions on decision-making in soccer. *Unpublished manuscript*.

Beavan, A., Fransen, J., Spielmann, J., Mayer, J., Skorski, S., & Meyer, T. (2018). The Footbonaut as a new football-specific skills test: reproducibility and age-related differences in highly trained youth players. *Science and Medicine in Football, 3*(3), 177-182.

Beavan, A., Spielmann, J., Mayer, J., Skorski, S., Meyer, T., & Fransen, J. (2019). Age-Related Differences in Executive Functions Within High-Level Youth Soccer Players. *Brazilian Journal of Motor Behavior, 13*(2), 64-75. doi:https://doi.org/10.20338/bjmb.v13i2.131

Beavan, A., Spielmann, J., Mayer, J., Skorski, S., Meyer, T., & Fransen, J. (2020). The rise and fall of executive functions in high-level football players. *Psychology of Sport and Exercise*, 101677.

Beilock, S. L., Bertenthal, B. I., Hoerger, M., & Carr, T. H. (2008). When does haste make waste? Speed-accuracy tradeoff, skill level, and the tools of the trade. *Journal of Experimental Psychology: Applied, 14*(4), 340.

Beilock, S. L., & Carr, T. H. (2001). On the fragility of skilled performance: What governs choking under pressure? *Journal of experimental psychology: General, 130*(4), 701.

Beilock, S. L., Jellison, W. A., Rydell, R. J., McConnell, A. R., & Carr, T. H. (2006). On the causal mechanisms of stereotype threat: Can skills that don't rely heavily on working memory still be threatened? *Personality and Social Psychology Bulletin, 32*(8), 1059-1071.

Belling, P. K., Suss, J., & Ward, P. (2015). Advancing theory and application of cognitive research in sport: Using representative tasks to explain and predict skilled anticipation, decision-making, and option-generation behavior. *Psychology of Sport and Exercise, 16*, 45-59.

Berry, J., Abernethy, B., & Côté, J. (2008). The contribution of structured activity and deliberate play to the development of expert perceptual and decision-making skill. *Journal of Sport and Exercise Psychology, 30*(6), 685-708.

Best, J. R., & Miller, P. H. (2010). A developmental perspective on executive function. *Child development, 81*(6), 1641-1660.

Bialystok, E., Craik, F. I., & Luk, G. (2012). Bilingualism: consequences for mind and brain. *Trends in cognitive sciences, 16*(4), 240-250.

Brand, M., Schiebener, J., Pertl, M.-T., & Delazer, M. (2014). Know the risk, take the win: How executive functions and probability processing influence advantageous decision making under risk conditions. *Journal of clinical and experimental neuropsychology, 36*(9), 914-929.

Buchheit, M. (2017). Houston, we still have a problem. *International journal of sports physiology and performance, 12*(8), 1111-1114. doi:https://doi.org/10.1123/ijspp.2017-0422

Buszard, T., Farrow, D., & Kemp, J. (2013). Examining the influence of acute instructional approaches on the decision-making performance of experienced team field sport players. *Journal of Sports Sciences, 31*(3), 238-247.

Chalkley, D., Shepherd, J. B., McGuckian, T. B., & Pepping, G.-J. (2018). Development and Validation of a Sensor-Based Algorithm for Detecting the Visual Exploratory Actions. *IEEE sensors letters, 2*(2), 1-4.

Chan, R. C., Shum, D., Toulopoulou, T., & Chen, E. Y. (2008). Assessment of executive functions: Review of instruments and identification of critical issues. *Archives of clinical neuropsychology, 23*(2), 201-216. doi:https://doi.org/10.1016/j.acn.2007.08.010

Chang, Y.-K., & Etnier, J. L. (2009). Exploring the dose-response relationship between resistance exercise intensity and cognitive function. *Journal of Sport and Exercise Psychology, 31*(5), 640-656. doi:https://doi.org/10.1123/jsep.31.5.640

Chase, W. G., & Simon, H. A. (1973). Perception in chess. *Cognitive Psychology, 4*(1), 55-81.

Cohen, J. (1988). Statistical power analysis for the behavioral sciences. 2nd: Hillsdale, NJ: erlbaum.

Colcombe, S., & Kramer, A. F. (2003). Fitness effects on the cognitive function of older adults: a meta-analytic study. *Psychological Science, 14*(2), 125-130. doi:https://doi.org/10.1111/1467-9280.t01-1-01430

Collie, A., Darby, D., & Maruff, P. (2001). Computerised cognitive assessment of athletes with sports related head injury. *British Journal of Sports Medicine, 35*(5), 297-302.

Congdon, E., Mumford, J. A., Cohen, J. R., Galvan, A., Canli, T., & Poldrack, R. A. (2012). Measurement and reliability of response inhibition. *Frontiers in Psychology, 3*, 37.

Côté, J., Baker, J., Abernethy, B., Starkes, J., & Ericsson, K. (2003). The development of elite athletes: Recent advances in research on sport expertise. *From play to practice: A developmental framework for the acquisition of expertise in team sport. Champaign, IL. Human Kinetics*, 89-113.

Côté, J., & Vierimaa, M. (2014). The developmental model of sport participation: 15 years after its first conceptualization. *Science & Sports, 29*, S63-S69.

Crone, E. A., Peters, S., & Steinbeis, N. (2017). Executive function development in adolescence *Executive Function* (pp. 58-72): Routledge.

Davids, K., & Araújo, D. (2010). The concept of 'Organismic Asymmetry'in sport science. *Journal of Science and Medicine in Sport, 13*(6), 633-640.

Davids, K., Williams, J. G., & Williams, A. M. (2005). Visual perception and action in sport.

Davis, C. L., Tomporowski, P. D., McDowell, J. E., Austin, B. P., Miller, P. H., Yanasak, N. E., . . . Naglieri, J. A. (2011). Exercise improves executive function and achievement and alters brain activation in overweight children: a randomized, controlled trial. *Health Psychology, 30*(1), 91.

De Groot, A. D. (1965). *Thought and choice in chess* (Vol. 4): Walter de Gruyter GmbH & Co KG.

De Luca, C. R., Wood, S. J., Anderson, V., Buchanan, J.-A., Proffitt, T. M., Mahony, K., & Pantelis, C. (2003). Normative data from the CANTAB. I: development of executive function over the lifespan. *Journal of clinical and experimental neuropsychology, 25*(2), 242-254.

Dehaene, S., Naccache, L., Le Clec'H, G., Koechlin, E., Mueller, M., Dehaene-Lambertz, G., . . . Le Bihan, D. (1998). Imaging unconscious semantic priming. *Nature, 395*(6702), 597. doi:https://doi.org/10.1038/26967

Dempster, F. N. (1992). The rise and fall of the inhibitory mechanism: Toward a unified theory of cognitive development and aging. *Developmental review, 12*(1), 45-75.

Dhami, M. K., Hertwig, R., & Hoffrage, U. (2004). The role of representative design in an ecological approach to cognition. *Psychological Bulletin, 130*(6), 959.

Diamond, A. (2002). Normal development of prefrontal cortex from birth to young adulthood: Cognitive functions, anatomy, and biochemistry. *Principles of frontal lobe function*, 466-503.

Diamond, A. (2013). Executive functions. *Annual review of psychology, 64*, 135-168. doi:https://doi.org/10.1146/annurev-psych-113011-143750

Diamond, A. (2016). Why improving and assessing executive functions early in life is critical. *Executive function in preschool-age children: Integrating measurement, neurodevelopment, and translational research*, 11-43.

Diamond, A., & Lee, K. (2011). Interventions shown to aid executive function development in children 4 to 12 years old. *Science, 333*(6045), 959-964.

Diamond, A., & Ling, D. (2017). Fundamental questions surrounding efforts to improve executive functions (including working memory). *An Integrative Approach to Cognitive andWorking Memory Training: Perspectives from Psychology, Neuroscience, and Human Development. Oxford University Press, New York, NY.*

Diamond, A., & Ling, D. S. (2016). Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not. *Developmental cognitive neuroscience, 18*, 34-48.

Diamond, A., & Ling, D. S. (2018). Aerobic-exercise and resistance-training interventions have been among the least effective ways to improve executive functions of any method tried thus far. *Dev. Cogn. Neurosci, 10*.

Dicks, M., Button, C., & Davids, K. (2010). Examination of gaze behaviors under in situ and video simulation task constraints reveals differences in information pickup for perception and action. *Attention, Perception, & Psychophysics, 72*(3), 706-720.

Dicks, M., Davids, K., & Button, C. (2009). Representative task design for the study of perception and action in sport. *International Journal of Sport Psychology, 40*(4), 506.

Drawer, S., & Fuller, C. (2002). Perceptions of retired professional soccer players about the provision of support services before and after retirement. *British Journal of Sports Medicine, 36*(1), 33-38.

Ducrocq, E., Wilson, M., Vine, S., & Derakshan, N. (2016). Training attentional control improves cognitive and motor task performance. *Journal of Sport and Exercise Psychology, 38*(5), 521-533.

Dunson, D. B. (2000). Bayesian latent variable models for clustered mixed outcomes. *Journal of the Royal Statistical Society: Series B (Statistical Methodology), 62*(2), 355-366.

Eisenmann, J. (2017). Translational gap between laboratory and playing field: new era to solve old problems in sports science. *Translational Journal of the American College of Sports Medicine, 2*(8), 37-43. doi:10.1249/TJX.0000000000000032

Eldridge, D., Pulling, C., & Robins, M. T. (2013). Visual exploratory activity and resultant behavioural analysis of youth midfield soccer players. *Journal of Human Sport and Exercise, 8*(3), 560-577.

Engelhardt, L. E., Harden, K. P., Tucker-Drob, E. M., & Church, J. A. (2019). The neural architecture of executive functions is established by middle childhood. *NeuroImage, 185*, 479-489.

Ericsson, K. A. (2014). Why expert performance is special and cannot be extrapolated from studies of performance in the general population: A response to criticisms. *Intelligence, 45*, 81-103.

Ericsson, K. A., & Charness, N. (1994). Expert performance: Its structure and acquisition. *American psychologist, 49*(8), 725.

Ericsson, K. A., Hoffman, R. R., & Kozbelt, A. (2018). *The Cambridge handbook of expertise and expert performance*: Cambridge University Press.

Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological Review, 102*(2), 211.

Ericsson, K. A., & Smith, J. (1991). Prospects and limits of the empirical study of expertise: An introduction. *Toward a General Theory of Expertise: Prospects and Limits, 344*.

Ericsson, K. A., & Ward, P. (2007). Capturing the naturally occurring superior performance of experts in the laboratory toward a science of expert and exceptional performance. *Current Directions in Psychological Science, 16*(6), 346-350.

Evans, J. D. (1996). *Straightforward statistics for the behavioral sciences*: Brooks/Cole.

Farrow, D., & Abernethy, B. (2002). Can anticipatory skills be learned through implicit video based perceptual training? *Journal of Sports Sciences, 20*(6), 471-485. doi:https://doi.org/10.1080/02640410252925143

Farrow, D., & Abernethy, B. (2003). Do expertise and the degree of perception—action coupling affect natural anticipatory performance? *Perception, 32*(9), 1127-1139.

Faubert, J. (2013a). Professional athletes have extraordinary skills for rapidly learning complex and neutral dynamic visual scenes. *Scientific Reports, 3*, 1154. doi:https://doi.org/10.1038/srep01154

Faubert, J. (2013b). Professional athletes have extraordinary skills for rapidly learning complex and neutral dynamic visual scenes. *Scientific Reports, 3*.

Faubert, J., & Sidebottom, L. (2012). Perceptual-cognitive training of athletes. *Journal of clinical sport psychology, 6*(1), 85-102. doi:https://doi.org/10.1123/jcsp.6.1.85

Fitts, P. M. (1964). Perceptual-motor skill learning *Categories of human learning* (pp. 243-285): Elsevier.

Flombaum, J. I., Scholl, B. J., & Pylyshyn, Z. W. (2008). Attentional resources in visual tracking through occlusion: The high-beams effect. *Cognition, 107*(3), 904-931.

Franks, I., Paterson, G., & Goodman, D. (1986). The real time analysis of sport: an overview. *Canadian journal of applied sport sciences. Journal canadien des sciences appliquees au sport, 11*(1), 55-57.

Fransen, J., Lovell, T. W., Bennett, K. J., Deprez, D., Deconinck, F. J., Lenoir, M., & Coutts, A. J. (2017). The Influence of Restricted Visual Feedback on Dribbling Performance in Youth Soccer Players. *Motor control, 21*(2), 158-167.

French, K., & McPherson, S. (1999). Adaptations in response selection processes used during sport competition with increasing age and expertise. *International Journal of Sport Psychology, 30*(2), 173-193.

French, K., & McPherson, S. (2004). Development of expertise in sport. *Developmental Sport and Exercise Psychology: A Lifespan Perspective*, 403-423.

Friedman, N. P., Miyake, A., Corley, R. P., Young, S. E., DeFries, J. C., & Hewitt, J. K. (2006). Not all executive functions are related to intelligence. *Psychological Science, 17*(2), 172-179.

Friedman, N. P., Miyake, A., Young, S. E., DeFries, J. C., Corley, R. P., & Hewitt, J. K. (2008). Individual differences in executive functions are almost entirely genetic in origin. *Journal of experimental psychology: General, 137*(2), 201-225. doi:https://doi.org/10.1037/0096-3445.137.2.201

Furley, P., & Memmert, D. (2012). Working memory capacity as controlled attention in tactical decision making. *Journal of Sport & Exercise Psychology, 34*(3), 322-344.

Furley, P., & Wood, G. (2016). Working memory, attentional control, and expertise in sports: A review of current literature and directions for future research. *Journal of Applied Research in Memory and Cognition, 5*(4), 415-425.

Gagné, F. (1985). Giftedness and talent: reexamining a reexamination of the definitions. *Gifted Child Quarterly, 29*, 103-112.

Gagné, F. (1999). My convictions about the nature of human abilities, gifts and talents. *Journal for the Education of the Gifted, 22*, 109-136.

Gagné, F. (2004). Transforming gifts into talents: The DMGT as a developmental theory. *High ability studies, 15*(2), 119-147. doi:https://doi.org/10.1080/1359813042000314682

Gelman, A., Carlin, J. B., Stern, H. S., Dunson, D. B., Vehtari, A., & Rubin, D. B. (2013). *Bayesian data analysis* (3rd ed.). London: Chapman and Hall/CRC.

Gorman, A. D., Abernethy, B., & Farrow, D. (2013). The expert advantage in dynamic pattern recall persists across both attended and unattended display elements. *Attention, Perception, & Psychophysics, 75*(5), 835-844.

Hambrick, D. Z., Macnamara, B. N., Campitelli, G., Ullén, F., & Mosing, M. A. (2016). Beyond born versus made: A new look at expertise *Psychology of Learning and Motivation* (Vol. 64, pp. 1-55): Elsevier.

Harris, D. J., Wilson, M. R., & Vine, S. J. (2018). A systematic review of commercial cognitive training devices: implications for use in sport. *Frontiers in Psychology, 9*, 709.

Hatfield, B. D., & Kerick, S. E. (2007). The psychology of superior sport performance. *Handbook of sport psychology. 3rd ed. Hoboken (NJ): Wiley*, 84-109.

Helsen, W., & Pauwels, J. (1993). The relationship between expertise and visual information processing in sport. *Advances in Psychology, 102*, 109-134.

Hendry, D. T., Williams, A. M., & Hodges, N. J. (2018). Coach ratings of skills and their relations to practice, play and successful transitions from youth-elite to adult-professional status in soccer. *Journal of Sports Sciences, 36*(17), 2009-2017.

Hill, M., Scott, S., Malina, R. M., McGee, D., & Cumming, S. P. (2019). Relative age and maturation selection biases in academy football. *Journal of Sports Sciences*, 1-9.

Hoaglin, D. C., Iglewicz, B., & Tukey, J. W. (1986). Performance of some resistant rules for outlier labeling. *Journal of the American Statistical Association, 81*(396), 991-999. doi:10.1080/01621459.1986.10478363

Hohmann, T., Obelöer, H., Schlapkohl, N., & Raab, M. (2015). Does training with 3D videos improve decision-making in team invasion sports? *Journal of Sports Sciences, 34*(8), 1-10.

Houwen, S., Visscher, C., Hartman, E., & Lemmink, K. A. (2007). Gross motor skills and sports participation of children with visual impairments. *Research Quarterly for Exercise and Sport, 78*(2), 16-23.

Howard, S. J., Vella, S. A., & Cliff, D. P. (2018). Children's sports participation and self-regulation: Bi-directional longitudinal associations. *Early Childhood Research Quarterly, 42*, 140-147.

Huijgen, B. C., Elferink-Gemser, M. T., Post, W., & Visscher, C. (2010). Development of dribbling in talented youth soccer players aged 12–19 years: A longitudinal study. *Journal of Sports Sciences, 28*(7), 689-698.

Huijgen, B. C., Leemhuis, S., Kok, N. M., Verburgh, L., Oosterlaan, J., Elferink-Gemser, M. T., & Visscher, C. (2015). Cognitive functions in elite and sub-elite youth soccer players aged 13 to 17 years. *PLoS One, 10*(12), e0144580.

Huijgen, B. C. H. (2013). *Technical skills, the key to succes? A study on talent development and selection of youth soccer players*.

Huizinga, M., Dolan, C. V., & van der Molen, M. W. (2006). Age-related change in executive function: Developmental trends and a latent variable analysis. *Neuropsychologia, 44*(11), 2017-2036. doi:https://doi.org/10.1016/j.neuropsychologia.2006.01.010

Huizinga, M., & Smidts, D. P. (2010). Age-related changes in executive function: A normative study with the Dutch version of the Behavior Rating Inventory of Executive Function (BRIEF). *Child neuropsychology, 17*(1), 51-66.

Impellizzeri, F. M., & Marcora, S. M. (2009). Test validation in sport physiology: lessons learned from clinimetrics. *International journal of sports physiology and performance, 4*(2), 269-277.

Ishihara, T., Sugasawa, S., Matsuda, Y., & Mizuno, M. (2017). Improved executive functions in 6–12-year-old children following cognitively engaging tennis lessons. *Journal of Sports Sciences, 35*(20), 2014-2020. doi:https://doi.org/10.1080/02640414.2016.1250939

Ishihara, T., Sugasawa, S., Matsuda, Y., & Mizuno, M. (2018). Relationship between sports experience and executive function in 6–12-year-old children: independence from physical fitness and moderation by gender. *Developmental science, 21*(3), e12555.

Ivens, C. J., & Marteniuk, R. G. (1997). Increased sensitivity to changes in visual feedback with practice. *Journal of Motor Behavior, 29*(4), 326-338.

Jacobson, J., & Matthaeus, L. (2014). Athletics and executive functioning: How athletic participation and sport type correlate with cognitive performance. *Psychology of Sport and Exercise, 15*(5), 521-527. doi:https://doi.org/10.1016/j.psychsport.2014.05.005

Jauk, E., Benedek, M., Dunst, B., & Neubauer, A. C. (2013). The relationship between intelligence and creativity: New support for the threshold hypothesis by means of empirical breakpoint detection. *Intelligence, 41*(4), 212-221.

Jewsbury, P., Bowden, S., & Strauss, M. (2015). Confirmatory factor analysis of executive function models: A Cattell-Horn-Carroll based reanalysis. *Submitted for publication*.

Johnson, J. G., & Raab, M. (2003). Take the first: Option-generation and resulting choices. *Organizational Behavior and Human Decision Processes, 91*(2), 215-229.

Jordet, G., Bloomfield, J., & Heijmerikx, J. (2013). *The hidden foundation of field vision in English Premier League (EPL) soccer players.* Paper presented at the Proceedings of the MIT sloan sports analytics conference.

Kahneman, D., & Klein, G. (2009). Conditions for intuitive expertise: a failure to disagree. *American psychologist, 64*(6), 515.

Karwowski, M., & Gralewski, J. (2013). Threshold hypothesis: Fact or artifact? *Thinking Skills and Creativity, 8*, 25-33. doi:https://doi.org/10.1016/j.tsc.2012.05.003

Katwala, A. (2016). *The Athletic brain: How neuroscience is revolutionising sport and can help you perform better*: Simon and Schuster.

Kibele, A. (2006). Non-consciously controlled decision making for fast motor reactions in sports—A priming approach for motor responses to non-consciously perceived movement features. *Psychology of Sport and Exercise, 7*(6), 591-610. doi:https://doi.org/10.1016/j.psychsport.2006.05.001

Kida, N., Oda, S., & Matsumura, M. (2005). Intensive baseball practice improves the Go/Nogo reaction time, but not the simple reaction time. *Cognitive brain research, 22*(2), 257-264. doi:https://doi.org/10.1016/j.cogbrainres.2004.09.003

Kramer, A. F., & Erickson, K. I. (2007). Capitalizing on cortical plasticity: influence of physical activity on cognition and brain function. *Trends in cognitive sciences, 11*(8), 342-348. doi:https://doi.org/10.1016/j.tics.2007.06.009

Krause, L., Farrow, D., Reid, M., Buszard, T., & Pinder, R. (2018). Helping coaches apply the principles of representative learning design: validation of a tennis specific practice assessment tool. *Journal of Sports Sciences, 36*(11), 1277-1286.

Krenn, B., Finkenzeller, T., Würth, S., & Amesberger, G. (2018). Sport type determines differences in executive functions in elite athletes. *Psychology of Sport and Exercise, 38*, 72-79. doi:https://doi.org/10.1016/j.psychsport.2018.06.002

Lai, M.-L., Tsai, M.-J., Yang, F.-Y., Hsu, C.-Y., Liu, T.-C., Lee, S. W.-Y., . . . Tsai, C.-C. (2013). A review of using eye-tracking technology in exploring learning from 2000 to 2012. *Educational Research Review, 10*, 90-115.

Lapierre, M. D., Cropper, S. J., & Howe, P. D. (2017). Shared processing in multiple object tracking and visual working memory in the absence of response order and task order confounds. *PLoS One, 12*(4).

Le Moal, E., Rué, O., Ajmol, A., Abderrahman, A. B., Hammami, M. A., Ounis, O. B., . . . Zouhal, H. (2014). Validation of the Loughborough Soccer Passing Test in young soccer players. *The Journal of Strength & Conditioning Research, 28*(5), 1418-1426.

Levitin, D. (2014). *The Organized Mind: Thinking Straight in the Age of Information*. United States: Dutton Penguin.

Leyhr, D., Kelava, A., Raabe, J., & Höner, O. (2018). Longitudinal motor performance development in early adolescence and its relationship to adult success: An 8-year prospective study of highly talented soccer players. *PLoS One, 13*(5), e0196324.

Li, S.-C., Lindenberger, U., Hommel, B., Aschersleben, G., Prinz, W., & Baltes, P. B. (2004). Transformations in the couplings among intellectual abilities and constituent cognitive processes across the life span. *Psychological Science, 15*(3), 155-163. doi:https://doi.org/10.1111/j.0956-7976.2004.01503003.x

Lichtenstein, J. D., Erdodi, L. A., Rai, J. K., Mazur-Mosiewicz, A., & Flaro, L. (2018). Wisconsin Card Sorting Test embedded validity indicators developed for adults can be extended to children. *Child neuropsychology, 24*(2), 247-260.

Ljac, V., Witkowski, Z., Gutni, B., Samovarov, A., & Nash, D. (2012). Toward effective forecast of professionally important sensorimotor cognitive abilities of young soccer players. *Perceptual and motor skills, 114*(2), 485-506. doi:https://doi.org/10.2466/05.10.25.PMS.114.2.485-506

Lohse, K. R., Sherwood, D. E., & Healy, A. F. (2010). How changing the focus of attention affects performance, kinematics, and electromyography in dart throwing. *Human Movement Science, 29*(4), 542-555.

Luna, B. (2009). Developmental changes in cognitive control through adolescence. *Advances in child development and behavior, 37*, 233-278. doi:https://doi.org/10.1016/S0065-2407(09)03706-9

Lundgren, T., Högman, L., Näslund, M., & Parling, T. (2016). Preliminary investigation of executive functions in elite ice hockey players. *Journal of clinical sport psychology, 10*(4), 324-335. doi:https://doi.org/10.1123/jcsp.2015-0030

Lyons, B. D., Hoffman, B. J., & Michel, J. W. (2009). Not much more than g? An examination of the impact of intelligence on NFL performance. *Human Performance, 22*(3), 225-245.

MacMahon, C., McPherson, S. L., & Farrow, D. (2009). *Knowledge base as a mechanism for perceptual-cognitive tasks: Skill is in the details!* Paper presented at the International Journal of Sport Psychology.

Macnamara, B. N., Hambrick, D. Z., & Oswald, F. L. (2018). Corrigendum: Deliberate practice and performance in music, games, sports, education, and professions: A meta-analysis.

Magnusson, K. (2014). Interpreting Cohen’s d effect size, an interactive visualization. Retrieved from https://rpsychologist.com/d3/cohend/

Malina, R. M., Bouchard, C., & Bar-Or, O. (2004). *Growth, maturation, and physical activity*: Human kinetics.

Malina, R. M., Ribeiro, B., Aroso, J., & Cumming, S. P. (2007). Characteristics of youth soccer players 13-15 years classified by skill level. *British Journal of Sports Medicine*.

Mann, D. L., Dehghansai, N., & Baker, J. (2017). Searching for the elusive gift: advances in talent identification in sport. *Current Opinion in Psychology, 16*, 128-133.

Mann, D. L., Farrow, D., Shuttleworth, R., Hopwood, M., & MacMahon, C. (2009). *The influence of viewing perspective on decision-making and visual search behaviour in an invasive sport.* Paper presented at the International Journal of Sport Psychology.

Mann, D. T., Williams, A. M., Ward, P., & Janelle, C. M. (2007). Perceptual-cognitive expertise in sport: A meta-analysis. *Journal of Sport and Exercise Psychology, 29*(4), 457-478.

Marteniuk, R. G. (1976). *Information processing in motor skills*: Holt, Rinehart and Winston.

Mayr, U., Spieler, D., & Kliegl, R. (2001). Ageing and executive control: Introduction to this special issue. *European Journal of Cognitive Psychology, 13*(1/2), 1-4.

McDermott, G., Burnett, A. F., & Robertson, S. J. (2015). Reliability and validity of the loughborough soccer passing test in adolescent males: Implications for talent identification. *International journal of Sports Science & Coaching, 10*(2-3), 515-527.

McDowd, J. M., & Shaw, R. J. (2000). Attention and aging: A functional perspective.

McGuckian, T. B., Beavan, A., Mayer, J., Chalkley, D., & Pepping, G.-J. (In press). The association between visual exploration and passing performance in high-level U13 and U23 football players. *Science and Medicine in Football*.

McGuckian, T. B., Cole, M. H., Chalkley, D., Jordet, G., & Pepping, G.-J. (2018a). Visual Exploration When Surrounded by Affordances: Frequency of Head Movements Is Predictive of Response Speed. *Ecological Psychology*, 1-19.

McGuckian, T. B., Cole, M. H., Chalkley, D., Jordet, G., & Pepping, G.-J. (2018b). Visual exploration when surrounded by affordances: Frequency of head movements is predictive of response speed. *Ecological Psychology*. doi:10.1080/10407413.2018.1495548

McGuckian, T. B., & Pepping, G.-J. (2016). A Wearable Inertial Sensor for Improved Measurement of Exploration Behaviour in Sport Compared to Notational Analysis. *Journal of Fitness Research, 5*.

Memmert, D. (2006). The effects of eye movements, age, and expertise on inattentional blindness. *Consciousness and Cognition, 15*(3), 620-627.

Memmert, D., Simons, D. J., & Grimme, T. (2009). The relationship between visual attention and expertise in sports. *Psychology of Sport and Exercise, 10*(1), 146-151.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual review of neuroscience, 24*(1), 167-202. doi:https://doi.org/10.1146/annurev.neuro.24.1.167

Moffitt, T. E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H., . . . Ross, S. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. *Proceedings of the National Academy of Sciences, 108*(7), 2693-2698.

Montuori, S., D'Aurizio, G., Foti, F., Liparoti, M., Lardone, A., Pesoli, M., . . . Sorrentino, P. (2019). Executive functioning profiles in elite volleyball athletes: Preliminary results by a sport-specific task switching protocol. *Human Movement Science, 63*, 73-81.

Nakamoto, H., & Mori, S. (2008). Effects of stimulus–response compatibility in mediating expert performance in baseball players. *Brain Research, 1189*, 179-188. doi:https://doi.org/10.1016/j.brainres.2007.10.096

Nédélec, M., McCall, A., Carling, C., Legall, F., Berthoin, S., & Dupont, G. (2012). Recovery in Soccer. *Sports Medicine, 42*(12), 997-1015.

Neumann, O., & Klotz, W. (1994). Motor responses to nonreportable, masked stimuli: Where is the limit of direct parameter specification. *Attention and performance XV: Conscious and nonconscious information processing*, 123-150.

Nougier, V., Stein, J.-F., & Bonnel, A.-M. (1991). Information processing in sport and" orienting of attention.". *International Journal of Sport Psychology*.

Oden, M. H. (1968). *The fulfillment of promise: 40 year follow up of the Terman gifted group* (Vol. 77): Stanford University Press.

Okada, B. M., & Slevc, L. R. (2018). Individual differences in musical training and executive functions: A latent variable approach. *Memory & cognition, 46*(7), 1076-1092.

Oppici, L., Panchuk, D., Serpiello, F. R., & Farrow, D. (2017). Long-term practice with domain-specific task constraints influences perceptual skills. *Frontiers in Psychology, 8*, 1387.

Phillips, E., Davids, K., Renshaw, I., & Portus, M. (2010). Expert performance in sport and the dynamics of talent development. *Sports Medicine, 40*(4), 271-283.

Pinder, R. A., Davids, K. W., Renshaw, I., & Araújo, D. (2011). Representative learning design and functionality of research and practice in sport. *Journal of Sport and Exercise Psychology, 33*(1), 146-155.

Pinder, R. A., Renshaw, I., Headrick, J., & Davids, K. (2013). Skill acquisition and representative task design *Complex systems in sport* (pp. 345-359): Routledge.

Poplu, G., Baratgin, J., Mavromatis, S., & Ripoll, H. (2003). What kind of processes underlie decision making in soccer simulation? An implicit-memory investigation. *International Journal of Sport and Exercise Psychology, 1*(4), 390-405.

Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of experimental psychology: General, 109*(2), 160. doi:http://dx.doi.org/10.1037/0096-3445.109.2.160

Proteau, L., & Cournoyer, J. (1990). Vision of the stylus in a manual aiming task: The effects of practice. *The Quarterly Journal of Experimental Psychology, 42*(4), 811-828.

Proteau, L., & Marteniuk, R. G. (1993). Static visual information and the learning and control of a manual aiming movement. *Human Movement Science, 12*(5), 515-536.

Proteau, L., Marteniuk, R. G., Girouard, Y., & Dugas, C. (1987). On the type of information used to control and learn an aiming movement after moderate and extensive training. *Human Movement Science, 6*(2), 181-199.

Proteau, L., Marteniuk, R. G., & Lévesque, L. (1992). A sensorimotor basis for motor learning: Evidence indicating specificity of practice. *The Quarterly Journal of Experimental Psychology Section A, 44*(3), 557-575.

Proust, C., Jacqmin-Gadda, H., Taylor, J. M., Ganiayre, J., & Commenges, D. (2006). A nonlinear model with latent process for cognitive evolution using multivariate longitudinal data. *Biometrics, 62*(4), 1014-1024.

Robert, C., & Casella, G. (2004). *Monte Carlo statistical methods* (2nd ed.). New York: Springer-Verlag.

Roca, A., Williams, A. M., & Ford, P. R. (2012). Developmental activities and the acquisition of superior anticipation and decision making in soccer players. *Journal of Sports Sciences, 30*(15), 1643-1652.

Romeas, T., Guldner, A., & Faubert, J. (2016). 3D-Multiple Object Tracking training task improves passing decision-making accuracy in soccer players. *Psychology of Sport and Exercise, 22*, 1-9.

Rostgaard, T., Iaia, F. M., Simonsen, D. S., & Bangsbo, J. (2008). A test to evaluate the physical impact on technical performance in soccer. *The Journal of Strength & Conditioning Research, 22*(1), 283-292.

Sajadi, N., & Rahnama, N. (2007). Analysis of goals in 2006 FIFA World Cup. *J Sports Sci Med, 6*(Suppl 10), 3.

Sakamoto, S., Takeuchi, H., Ihara, N., Ligao, B., & Suzukawa, K. (2018). Possible requirement of executive functions for high performance in soccer. *PLoS One, 13*(8), e0201871. doi:https://doi.org/10.1371/journal.pone.0201871

Saygin, O., Goral, K., & Ceylan, H. I. (2016). An examination of the coincidence anticipation performance of soccer players according to their playing positions and different stimulus speeds. *Sport Journal, 1*, 1-12.

Scharfen, H. E., & Memmert, D. (2019). Measurement of Cognitive Functions in Experts and Elite-Athletes: A Meta-Analytic Review. *Applied Cognitive Psychology, 33*(5), 843-860. doi:https://doi.org/10.1002/acp.3526

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82*(4), 225.

Schuhfried, G. (2001). Sport psychology. Sport test battery for diagnostics and training: Mödling: Dr. Schuhfried Ges.m.b.H.

Serpiello, F., Cox, A., Oppici, L., Hopkins, W., & Varley, M. (2017). The Loughborough Soccer Passing Test has impractical criterion validity in elite youth football. *Science and Medicine in Football, 1*(1), 60-64.

Simon, H. A. (1992). What is an “explanation” of behavior? *Psychological Science, 3*(3), 150-161.

Simons, D. J., Boot, W. R., Charness, N., Gathercole, S. E., Chabris, C. F., Hambrick, D. Z., & Stine-Morrow, E. A. (2016). Do “brain-training” programs work? *Psychological Science in the Public Interest, 17*(3), 103-186.

Smith, T. Q., & Mitroff, S. R. (2012). Stroboscopic training enhances anticipatory timing. *International journal of exercise science, 5*(4), 344.

Stiroh, K. J. (2007). Playing for Keeps: Pay and Performance in the NBA. *Economic Inquiry, 45*(1), 145-161. doi:https://doi.org/10.1111/j.1465-7295.2006.00004.x

Strand, B. N., & Wilson, R. (1993). *Assessing sport skills*.

Stratton, G. (2004). *Youth soccer: From science to performance*: Psychology Press.

Sunderland, C., Cooke, K., Milne, H., & Nevill, M. (2006). The reliability and validity of a field hockey skill test. *International journal of sports medicine, 27*(05), 395-400.

Terman, L. M., Baldwin, B. T., Bronson, E., & De Voss, J. C. (1926). *Mental and physical traits of a thousand gifted children* (Vol. 1): Stanford University Press Stanford, CA.

Terman, L. M., & Oden, M. H. (1947). The gifted child grows up: Twenty-five years' follow-up of a superior group.

Terman, L. M., & Oden, M. H. (1959). Genetic studies of genius. Vol. V. The gifted group at mid-life.

Thomas, C., Fellingham, G., & Vehrs, P. (2009). Development of a notational analysis system for selected soccer skills of a women's college team. *Measurement in Physical Education and Exercise Science, 13*(2), 108-121.

Tijtgat, P., Bennett, S. J., Savelsbergh, G. J., De Clercq, D., & Lenoir, M. (2010). Advance knowledge effects on kinematics of one-handed catching. *Experimental Brain Research, 201*(4), 875-884.

Travassos, B., Araujo, D., Davids, K., O'hara, K., Leitão, J., & Cortinhas, A. (2013). Expertise effects on decision-making in sport are constrained by requisite response behaviours–A meta-analysis. *Psychology of Sport and Exercise, 14*(2), 211-219. doi:https://doi.org/10.1016/j.psychsport.2012.11.002

Travassos, B., Araújo, D., Davids, K., O'Hara, K., Leitao, J., & Cortinhas, A. (2013). Expertise effects on decision-making in sport are constrained by requisite response behaviours–A meta-analysis. *Psychology of Sport and Exercise, 14*(2), 211-219.

Uchida, Y., Kudoh, D., Higuchi, T., Honda, M., & Kanosue, K. (2013). Dynamic visual acuity in baseball players is due to superior tracking abilities. *Medicine and Science in Sports and Exercise, 45*(2), 319-325.

Unsworth, N., Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior research methods, 37*(3), 498-505.

Vaeyens, R., Lenoir, M., Williams, A. M., Mazyn, L., & Philippaerts, R. M. (2007). The effects of task constraints on visual search behavior and decision-making skill in youth soccer players. *Journal of Sport and Exercise Psychology, 29*(2), 147.

Vaeyens, R., Lenoir, M., Williams, A. M., & Philippaerts, R. M. (2007). Mechanisms underpinning successful decision making in skilled youth soccer players: An analysis of visual search behaviors. *Journal of Motor Behavior, 39*(5), 395-408.

Vaeyens, R., Malina, R. M., Janssens, M., Van Renterghem, B., Bourgois, J., Vrijens, J., & Philippaerts, R. M. (2006). A multidisciplinary selection model for youth soccer: the Ghent Youth Soccer Project. *British Journal of Sports Medicine, 40*(11), 928-934.

van Maarseveen, M. J., Oudejans, R. R., Mann, D. L., & Savelsbergh, G. J. (2016). Perceptual-cognitive skill and the in situ performance of soccer players. *The Quarterly Journal of Experimental Psychology*, 1-17.

VandenBos, G. R. (2007). *APA dictionary of psychology*: American Psychological Association.

Verburgh, L., Königs, M., Scherder, E. J., & Oosterlaan, J. (2014). Physical exercise and executive functions in preadolescent children, adolescents and young adults: a meta-analysis. *Br J Sports Med, 48*(12), 973-979.

Verburgh, L., Scherder, E. J., van Lange, P. A., & Oosterlaan, J. (2014). Executive functioning in highly talented soccer players. *PLoS One, 9*(3), e91254. doi:https://doi.org/10.1371/journal.pone.0091254

Verburgh, L., Scherder, E. J., Van Lange, P. A., & Oosterlaan, J. (2016). Do Elite and Amateur Soccer Players Outperform Non-Athletes on Neurocognitive Functioning? A Study Among 8-12 Year Old Children. *PLoS One, 11*(12), e0165741. doi:https://doi.org/10.1371/journal.pone.0165741

Vestberg, T., Gustafson, R., Maurex, L., Ingvar, M., & Petrovic, P. (2012). Executive functions predict the success of top-soccer players. *PLoS One, 7*(4), e34731. doi:https://doi.org/10.1371/journal.pone.0034731

Vestberg, T., Reinebo, G., Maurex, L., Ingvar, M., & Petrovic, P. (2017). Core executive functions are associated with success in young elite soccer players. *PLoS One, 12*(2), e0170845. doi:https://doi.org/10.1371/journal.pone.0170845

Vilar, L., Araújo, D., Davids, K., & Renshaw, I. (2012). The need for 'representative task design'in evaluating efficacy of skills tests in sport: A comment on Russell, Benton and Kingsley (2010). *Journal of Sports Sciences, 30*(16), 1727-1730.

Vorberg, D., Mattler, U., Heinecke, A., Schmidt, T., & Schwarzbach, J. (2003). Different time courses for visual perception and action priming. *Proceedings of the National Academy of Sciences, 100*(10), 6275-6280. doi:https://doi.org/10.1073/pnas.0931489100

Voss, M. W., Kramer, A. F., Basak, C., Prakash, R. S., & Roberts, B. (2010). Are expert athletes 'expert'in the cognitive laboratory? A meta-analytic review of cognition and sport expertise. *Applied Cognitive Psychology, 24*(6), 812-826. doi:https://doi.org/10.1002/acp.1588

Walton, C. C., Keegan, R. J., Martin, M., & Hallock, H. (2018). The potential role for cognitive training in sport: more research needed. *Frontiers in Psychology, 9*.

Wang, C.-H., Tsai, C.-L., Tu, K.-C., Muggleton, N. G., Juan, C.-H., & Liang, W.-K. (2015). Modulation of brain oscillations during fundamental visuo-spatial processing: a comparison between female collegiate badminton players and sedentary controls. *Psychology of Sport and Exercise, 16*, 121-129.

Wang, C.-H., & Tu, K.-C. (2017). Neural correlates of expert behavior during a domain-specific attentional cueing task in badminton players. *Journal of Sport and Exercise Psychology, 39*(3), 209-221.

Ward, P., & Williams, A. M. (2003). Perceptual and cognitive skill development in soccer: The multidimensional nature of expert performance. *Journal of Sport and Exercise Psychology, 25*(1), 93-111. doi:https://doi.org/10.1123/jsep.25.1.93

Ward, P., Williams, A. M., & Bennett, S. J. (2002). Visual search and biological motion perception in tennis. *Research Quarterly for Exercise and Sport, 73*(1), 107-112.

Warshawsky-Livne, L., & Shinar, D. (2002). Effects of uncertainty, transmission type, driver age and gender on brake reaction and movement time. *Journal of safety research, 33*(1), 117-128. doi:https://doi.org/10.1016/S0022-4375(02)00006-3

Weinberg, R. S., & Gould, D. (2014). *Foundations of Sport and Exercise Psychology, 6E*: Human Kinetics.

Whiteside, A., Parker, G., & Snodgrass, R. (2003). A review of selected tests from the Vienna Test System. *Selection and Development Review, 19*(4), 7-11.

Whiting, H., Savelsbergh, G., & Pijpers, J. (1995). Specificity of motor learning does not deny flexibility. *Applied Psychology, 44*(4), 315-332.

Wickens, C. D., & McCarley, J. S. (2007). *Applied attention theory*: CRC press.

Williams, A. M. (2000). Perceptual skill in soccer: Implications for talent identification and development. *Journal of Sports Sciences, 18*(9), 737-750.

Williams, A. M., & Ericsson, K. A. (2005). Perceptual-cognitive expertise in sport: Some considerations when applying the expert performance approach. *Human Movement Science, 24*(3), 283-307.

Williams, A. M., & Ward, P. (2007). Anticipation and decision making: Exploring new horizons. *Handbook of Sport Psychology, Third Edition*, 203-223.

Williams, A. M., Ward, P., Knowles, J. M., & Smeeton, N. J. (2002). Anticipation skill in a real-world task: measurement, training, and transfer in tennis. *Journal of Experimental Psychology: Applied, 8*(4), 259-270.

Wilson, R. S., Bennett, D., Bienias, J., De Leon, C. M., Morris, M., & Evans, D. (2003). Cognitive activity and cognitive decline in a biracial community population. *Neurology, 61*(6), 812-816.

Winnick, J. P. (1985). The performance of visually impaired youngsters in physical education activities: Implications for mainstreaming. *Adapted Physical Activity Quarterly, 2*(4), 292-299.

Winter, E. M., & Maughan, R. J. (2009). Requirements for ethics approvals: Taylor & Francis.

Zelazo, P. D., & Carlson, S. M. (2012). Hot and cool executive function in childhood and adolescence: Development and plasticity. *Child development perspectives, 6*(4), 354-360.

Zelazo, P. D., Craik, F. I., & Booth, L. (2004). Executive function across the life span. *Acta Psychologica, 115*(2-3), 167-183. doi:https://doi.org/10.1016/j.actpsy.2003.12.005

Zelazo, P. D., & Müller, U. (2002). *Executive function in typical and atypical development* (In U. Goswami (Ed.) ed.). Oxford, England: Blackwell Publishers.

Zelazo, P. D., Müller, U., Frye, D., & Marcovitch, S. (2003). The development of executive function in early childhood: I. The development of executive function. *Monographs of the society for research in child development*. doi:https://doi.org/10.1111/j.0037-976X.2003.00261.x

Tag der Promotion: 29. April. 2021

Dekan: Uni.-Prof. Dr. med. Michael D. Menger

Bericherstatter: Prof. Dr. med Tim Meyer
Prof. Dr. Oliver Höner
Dr. Greg Wood