A MULTIDIMENSIONAL PERSPECTIVE ON COGNITIVE FUNCTIONING ACROSS SPORT CLASSIFICATIONS IN HIGH-PERFORMANCE ATHLETES

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A THESIS SUBMITTED TO THE DEPARTMENT OF PSYCHOLOGY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF ARTS

GRADUATE PROGRAM IN PSYCHOLOGY

YORK UNIVERSITY

TORONTO, ONTARIO

MAY 2025

Abstract

This thesis presents a comprehensive investigation into the domain-general cognitive functioning of high-performance athletes, addressing inconsistencies in current assessment methods. The sample consisted of 188 athletes from the Canadian Sport Institute of Ontario from Team (n=94), Precision/Skill-dependent (n=56), and Speed-strength (n=28) sports. Athletes completed a battery of computerized neuropsychological tests. Study 1 examined multidimensional cognitive profiles. Athletes exhibited superior performance, with associations found between episodic memory, visuospatial working memory, attention/concentration, and verbal reasoning. Two latent factors—attention/executive function and short-term (working) emerged. Study 2 examined cognitive performance across sport type. Team sport athletes outperformed those in other sports on visual short-term (working) memory, response inhibition, visuospatial working memory, and working memory tasks. They also secured the highest proportion of high scores across increasing thresholds. Collectively, the current thesis provides a foundation for future research to advance athlete cognitive profiling to inform talent identification and development strategies.

Keywords: Multidimensional cognitive profiles, Computerized neuropsychological test, Sport classification.

Acknowledgements

I would first like to thank my supervisor, Dr. Magdalena Wojtowicz, for her unwavering guidance and passion for advancing science in meaningful ways. From the moment I joined the lab as an undergraduate student, you have provided me with opportunities to grow—not only as a researcher but also as a person. For that, I am truly grateful.

Thank you to Dr. Joe Baker for his guidance and support throughout my masters. Your feedback has been immensely valuable in the completion of my final thesis.

To my parents, I am endlessly grateful for your unwavering support throughout my academic journey and life. Dad, you instilled in me discipline and determination, shaping my drive to succeed. Mom, your compassion and kindness have nurtured my ability to connect with others and grow as a researcher. The values you've taught me continue to guide me every step of the way.

Finally, to my fiancé, Cadance—your unwavering support and love have been my anchor through every challenge and triumph over the past four years. Your belief in me, even in the toughest moments, has given me the strength to persevere. I am endlessly grateful for your encouragement and patience that continues to guide me forward. I cannot wait to see where life takes us.

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Introduction

When examining factors that contribute to an athlete's performance at the highest level, the focus is often placed on physical abilities, technical skills, and perceptual-motor coordination (Chan, Wong, Liu, Yu, & Yan, 2011; Diamond & Ling, 2016; Frederiksen et al., 2015; Krenn et al., 2018). However, there is substantial evidence suggesting that athletes with higher levels of sport expertise exhibit superior domain-general cognitive abilities (Beavan et al., 2020; Chan et al., 2011; Cona et al., 2015; Diamond & Ling, 2016; Faubert, 2013; Krenn et al., 2018; Marchetti et al., 2015; Romeas et al., 2016; Verburgh et al., 2014; Vestberg et al., 2017). Domain-general cognitive abilities encompass various aspects of cognition, such as executive functioning (EF), attention, or processing speed, which are crucial for managing, and synthesizing information across diverse tasks and scenarios (Colman, 2019; Vona et al., 2024). These cognitive processes likely allow athletes to effectively adapt and integrate information, impacting their ability to make quick decisions and perform effectively under pressure.

Although performing in sport likely requires a wide range of cognitive demands, research has primarily focused on EF (i.e., working memory, cognitive flexibility, and inhibition; Albaladejo-García et al., 2023; Alves et al., 2013; Elferink-Gemser et al., 2018; Schiebener et al., 2013; Vaughan & Laborde, 2020; Vestberg et al., 2012; Voss et al., 2010). While these skills are essential for regulating behavior, adapting to changing situations, and planning goal-directed actions (Diamond, 2013), other cognitive domains, such as visuospatial skills, attention, and processing speed, have received comparatively less attention in research (Cona et al., 2015; Rahimi et al., 2022; Vestberg et al., 2012, 2017). These abilities may be particularly relevant in sports requiring rapid visual tracking, spatial awareness, and quick decision-making under varying conditions. While previous research has established a link between sport expertise and superior cognitive functioning, relatively few studies have examined how these cognitive advantages translate into on-field performance (Elferink-Gemser et al., 2018; Vestberg et al., 2017). Understanding the cognitive mechanisms underlying superior performance may provide critical insights into the cognitive demands of high-performance sport, ultimately informing training strategies that integrate cognitive development to optimize athletic success.

Theoretical Frameworks for Understanding Cognitive Functioning in High-Performance Athletes

Several theoretical frameworks have been proposed to explain the link between cognition and performance in athletes. These frameworks aim to explain the underlying mechanisms behind superior cognitive abilities in athletes, with two primary approaches - the expert performance approach and the cognitive component skills approach - reflecting the key assumptions of most frameworks. The expert performance approach posits that athletes' cognitive expertise is most visible in tasks that simulate real-world, sport-specific scenarios. These tasks can assess skills such as attention, perception, anticipation, and decision-making, which are crucial for navigating the demands of their sport (Logan et al., 2022; Singer, 2000; Voss et al., 2010). This approach underscores the importance of ecological validity in cognitive assessments, arguing that athletes' superior performance on sport-related tasks reflects their heightened cognitive abilities in contexts directly related to their field of expertise. However, a limitation of this approach is its narrow focus on tasks reflecting sport-specific skills, as this approach struggles to explain why athletes with greater sport expertise tend to perform better on more generalized cognitive tasks not related to their sport. Additionally, when tests are tailored to specific skills or sports, they may not be properly validated and fail to generalize to other sports. As a result, these approaches may overlook the broader cognitive abilities that contribute to athletic success. This gap further suggests that while the expert performance approach is valuable in understanding sport-specific cognitive abilities, it does not account for the broader, domain-general cognitive abilities that athletes may possess outside of sport contexts. In contrast, the cognitive component skills approach expands this perspective by focusing on the relationship between sport expertise and athlete's cognitive performance on tasks assessing domain-general cognitive abilities (Nougier et al., 1991; Voss et al., 2010). This approach considers athletes' inherent cognitive abilities that can be examined across athletes and sports, but it overlooks the specific cognitive demands of their training and performance in ecologically valid settings.

To bridge the gap between these two approaches, the broad transfer hypothesis offers further insight into the impact of sport-specific training on cognitive functioning. This hypothesis states that extensive, sustained training in a particular activity can lead to improvements in cognitive performance across a wide range of cognitive tasks, even those that are not directly related to the activity itself (Allen et al., 2011; Jacobson & Matthaeus, 2014; Voss et al., 2010). This theory is supported by four meta-analyses demonstrating that high levels of sport expertise are linked to superior performance not only on sport-specific tasks but also on domain-general cognitive tasks, including EF, attention, visuospatial processing, and processing speed (Kalén et al., 2021; Logan et al., 2022; Scharfen & Memmert, 2019; Voss et al., 2010). Furthermore, when looking at the role that physical activity has on athletes' cognitive performance, the cognitive development theory proposes that athletes' physical activity contributes to structural changes (e.g., neurogenesis) through a neurotrophic cascade. This process drives neuroplasticity and leads to functional adaptations, such as improvements in cognitive performance (Furley et al., 2023; Vona et al., 2024). Previous fMRI studies have demonstrated greater cortical thickness in athletes relative to non-athletes, increased plasma BDNF in high-performance athletes, as well as significant functional changes in performance on various cognitive tasks (Wei et al., 2011; Correia et al., 2011; Kramer et al., 1999; Tseng et al., 2013).

By integrating these approaches and hypotheses, a clearer framework emerges for understanding athletes' cognitive performance on domain-general tasks. The expert performance approach seeks to broadly explain athletes' superior performance in sport-specific tasks but fails to account for broader cognitive performance on tasks unrelated to athletes' particular sport. The cognitive component skills approach expands on this by highlighting athletes' superior performance on domain-general tasks but overlooks the influence of the ecological demands of sport. To bridge this gap, the broad transfer hypothesis suggests that superior cognitive functioning from sport-specific training can extend to non-sport-related tasks. Additionally, cognitive development theory highlights how physical activity induces structural changes in the brain (e.g., neurogenesis), fostering neuroplasticity and improving cognitive functions like EF and attention. These theories collectively emphasize the uncertainty around the causal relationship between sport demands and generalized cognitive performance, while also underscoring the need for a more comprehensive understanding of how sport-specific cognitive demands influence athletes' sport selection (Vona et al., 2024).

Approaches to Measuring Cognition and Classifying Cognitive Performance

To comprehensively assess cognitive functioning, various tools and approaches have been employed across diverse populations. Traditional assessments of cognition have relied on paper-and-pencil tests to evaluate a multitude of cognitive functions (e.g., EF, attention, and processing speed). These tests are often employed due to their reliability, ability to target specific cognitive domains, cost effectiveness, and the simplicity of administering these tests (Chan et al., 2018; Wilke et al., 2020). As a variety of pen-and-paper cognitive assessments have been employed to understand athletes cognitive functioning, there have been mixed findings (Barr, 2003; Chang et al., 2017; Heppe et al., 2016; Jacobson & Matthaeus, 2014; Scharfen & Memmert, 2019; Willer et al., 2018). For instance, some studies have found that athletes' cognitive performance is similar to that of a normative population (e.g., Prien et al., 2020; Tomczyk et al., 2018; Willer et al., 2018), while others suggest that athletes exhibit superior cognitive performance relative to non-athletes (Chan et al., 2018; Heppe et al., 2016; Legault et al., 2022). Variability in findings may arise from differences in sample characteristics, as well as the cognitive domain targeted by the assessment tool employed (Chang et al., 2017). One key limitation of employing pen-and-paper tests is the over-reliance on single-test thresholds to classify cognitive performance, which may oversimplify athletes' cognitive profiles and fail to account for the multidimensional nature of their cognitive abilities (Howieson, 2019). For instance, using a single score from the Stroop Color Test to determine an athlete's cognitive functioning may overlook individuals' strengths in other cognitive domains. Also, many traditional pen-and-paper tests do not capture moment-to-moment reaction time, which can be a highly sensitive indicator of subtle performance differences across individuals. This narrow approach does not capture the variability in cognitive performance that can exist among athletes, particularly when considering factors like sport-specific demands and individual strengths (Scharfen & Memmert, 2019). For this reason, a more holistic, multivariate approach to measure cognition is needed to better understand the cognitive profiles of athletes.

As a result of the limitations associated with traditional pen-and-paper assessments, a large proportion of studies assessing cognitive functioning in athletes have employed Computerized Neuropsychological Tests (CNTs; e.g., Kontos et al., 2010; Tomczyk et al., 2018;

Yao et al., 2024). CNTs offer a more dynamic approach to assessing domain-general cognitive functioning by allowing for a more detailed and comprehensive evaluation of cognitive functioning (Rahman-Filipiak & Woodard, 2013). As numerous pen-and-paper tests focus on a limited subset of cognitive domains, CNTs may allow researchers to assess a broad range of cognitive abilities across multiple cognitive domains. A comprehensive neuropsychological battery allows researchers to not only account for athlete's strengths and weaknesses in different aspects of cognition, but also captures the interplay across various cognitive domains, a factor often overlooked in pen-and-paper assessments (Scharfen & Memmert, 2019; Resch et al., 2013). An additional benefit of employing CNTs is that it provides real time performance metrics, while allowing researchers to track performance over time (Witt et al., 2013). Moreover, obtaining sufficiently powered sample sizes of high-performance athletes is often extremely challenging due to logistical constraints, and the need for specialized testing environments (Vona et al., 2024). However, CNTs offer a practical solution by allowing for remote testing, which allows for greater flexibility and accessibility. This capability helps overcome barriers associated with in-person testing while increasing sample sizes by facilitating the inclusion of individuals from diverse locations and backgrounds. When assessing the test-retest reliability between online vs. in-person testing, moderate reliability was demonstrated while participants also reported enjoyable testing experiences across a variety of neuropsychological batteries employed (Balit et al., 2024; Cyr et al., 2020; Morrissey et al., 2024; Sokołowski et al., 2024).

Exploring Sport Type on Athletes Cognitive Performance

While previous studies have emphasized the relationship between athlete expertise and superior performance on tasks measuring domain-general cognitive abilities (e.g., Burris et al., 2019; Diamond & Ling, 2019; Jacobson & Matthaeus, 2014; Wang et al., 2013), inconsistencies in laboratory-based cognitive assessments highlight the need for further investigation into athletes’ cognitive functioning (Scharfen & Memmert, 2019; Voss et al., 2010). For instance, research examining EF in youth soccer players has revealed non-significant effects across different levels of sport expertise (Beavan et al., 2020; Beavan, Spielmann, Ehmann, et al., 2022). These discrepancies may arise from factors such as small sample sizes, variations in task validity, evolving cognitive assessments, and the size of reported effects (Furley et al., 2023; Vona et al., 2024). Furthermore, issues like experimenter bias, publication bias, and methodological inconsistencies contribute to low statistical power, complicating the detection of specific group effects (Scharfen & Memmert, 2019; Schmidt, 1992; Vona et al., 2024). While much of the existing research has focused on EF, other critical cognitive processes such as visuospatial processing, attention, and working memory are often overlooked. Emerging evidence suggests that these domains not only contribute to athletic performance but may also improve with increased sport expertise. For example, a meta-analysis by Logan et al. (2022) revealed that athletes performed better than control groups on tasks measuring attentional allocation, with sport participation playing a significant role in athletes' cognitive performance. Additionally, Brimmell et al. (2022) suggested that EF may act as a mediator that can enhance visual attention performance.

In recent years, researchers have increasingly turned their attention to examining performance differences in cognitive tasks based on athletes' classification of sport. A widely used classification system is open skill and closed skill sports. Open skill sports require athletes to react in dynamic, changing, and unpredictable environments that are externally paced (e.g., hockey, soccer). In contrast, closed skill sports require athletes to engage in a highly consistent, predictable and self-paced sporting environments (Allard & Burnett, 1985; Singer, 2000). A more refined classification system was created that included three separate sport classifications: strategic, interceptive, and static (Voss et al., 2010). Strategic sports require athletes to adapt to highly varying situations while considering teammates, opponents and other objects in an externally paced environment (e.g., hockey, volleyball). Interceptive sports require athletes' dynamic coordination between their body and their environment (e.g., tennis). Static sports are self-paced activities in highly consistent circumstances (e.g., swimming). Lastly, the current thesis employs a more refined sport classification framework that incorporates athletes physiological, tactical, skill, and cognitive demands in their classification of sport. These sport groups include team, speed/strength and precision/skill-dependent sports (McKay et al., 2022). Team sports are dynamic and strategic, demanding athletes to process a constant influx of unpredictable information from teammates, opponents, and sport-specific elements (e.g., hockey puck, soccer ball). Athletes in these sports also need to exhibit exceptional endurance, agility, and strength to perform effectively. Speed and strength sports require athletes to generate maximum force in a brief period. These sports prioritize strength and velocity over precision during high-intensity movements (e.g., cycling, swimming). Precision/skill-dependent sports are characterized by the execution of highly coordinated, pre-planned routines that demand technical accuracy, artistic expression, and refined motor control. Athletes in these sports must demonstrate exceptional flexibility, balance, strength, and power to execute precise movements.

When looking at previous research that examines the relationship between sport classification and domain-general cognitive performance, athletes from strategic sports (e.g., hockey) outperform those from static sports (e.g., diving) in tasks like visuospatial working memory (Sato et al., 2022) and visual attention (Meng, Yao, Chang, & Chen, 2019). Researchers from both studies have attributed athletes' superior cognitive performance to the increased cognitive demands inherent in team sports. However, the relationship between sport type and cognitive performance remains inconsistent (De Waelle et al., 2021; Holfelder et al., 2020; Pačesová, 2021; Quinzi et al., 2022; Vona et al., 2024). These inconsistencies may arise from variations in sport classification. For instance, distinctions between open (externally paced) and closed (internally paced) skill sports demonstrate that open skill athletes outperform closed skill athletes on a multitude of tasks assessing domain-general cognitive functioning (Holfelder et al., 2020; Russo et al., 2022). When sport classifications are refined to include static, interceptive, or strategic categories (Mann et al., 2007; Voss et al., 2010), results become more mixed. Some studies indicate that team sports excel in processing speed (Voss et al., 2010), while others highlight advantages in EF and attention (Krenn et al., 2018; Meng et al., 2019). Further refinement of sport classifications (McKay et al., 2022) has demonstrated that athletes from speed/strength sports have superior cognitive flexibility compared to those from team and precision/skill-dependent sports (Vona et al., 2024).

Understanding Domain-General Cognitive Functioning through Multivariate Base Rates

When looking at cognitive performance on a domain-general cognitive battery, previous research has examined the prevalence of both high and low scores among a normative sample (Brooks et al., 2010; Brooks et al., 2012; Holdnack et al., 2017; Karr et al., 2016; Karr et al., 2019). The normal frequency of both high and low scores on a neuropsychological battery has been quantified as a psychometric principle referred to as multivariate base rates. Research on multivariate base rates has demonstrated three principles for both low and high scores: (1) high and low scores occur commonly among a normative population, (2) the number of low and high scores observed increases with the number of tests administered, (3) the number of high and low scores observed is contingent on the cutoff used to define a high (i.e., ≤75th percentile vs. ≤84th percentile) or low (i.e., ≤25th percentile vs. ≤16th percentile) scores (Brooks et al., 2013; Karr et al., 2019). As the majority of studies have assessed multivariate base rates of high and low scores on neuropsychological batteries (e.g., WAIS-IV, D-KEFS, and NIHTB-CB) among a normative population, no study to our knowledge has employed this methodology in an athlete population to assess domain-general cognitive functioning. As findings from multivariate base rates have primarily been employed in a clinical context, these results can have vast implications that can be used to understand athletes' cognitive profiles.

Despite the growing use of cognitive testing in sports for baseline profiling and concussion management, there is a notable gap in applying multivariate base rates in athlete populations. As athletes frequently take part in routine cognitive assessments during baseline and post-injury contexts, interpretations often rely on single-test thresholds rather than interpreting athletes' multivariate cognitive performance. Taking a multivariate perspective to understand athletes’ cognitive functioning can allow researchers to understand the interplay between different domains of cognition to create a more accurate assessment of athletes’ complete profile. As previous studies have highlighted that variability in cognitive performance can occur among athletes even in the absence of any pathology (e.g., concussion; Hernández-Mendo et al., 2019; Register-Mihalik et al., 2012), employing multivariate base rates can provide a more holistic approach to understanding athletes overall cognitive functioning.

The Current Research

Despite the growing interest in assessing cognitive functioning among high-performance athletes, inconsistencies in domain-general cognitive assessments and conflicting findings regarding cognitive performance across sport classifications underscore the need for a more comprehensive investigation. To address this gap, the current thesis takes a multidimensional approach to analyze domain-general cognitive functioning among high-performance athletes. Traditional methods often rely on mean-based outcomes, focusing on individual cognitive domains (e.g., EF) in isolation. This approach often overlooks the intricate interactions and interdependencies between various cognitive domains, which are critical for understanding athletes' cognitive profiles. To address this, Study 1 sought to examine the multidimensional cognitive profiles of high-performance athletes using CNTs that assess verbal short-term (working) memory, response inhibition, attention/concentration, verbal reasoning, visuospatial working memory, deductive reasoning, episodic memory, visuospatial processing, mental rotations, working memory, spatial working memory/ planning, and visual short-term (working) memory. Athletes' performance on tasks assessing these domains of cognition was also examined using multivariate base rates of high scores.

The goal of Study 2 was to apply this multidimensional perspective of cognitive functioning to examine performance differences on domain-general cognitive tasks among athletes from various sports. Building on existing research regarding open-skill and strategic sports (e.g., requirement to react to unpredictable situations and make rapid, adaptive decisions under dynamic conditions), we hypothesized that athletes from team sports would demonstrate superior cognitive performance compared to those in speed/strength and precision/skill-dependent sports across the assessed cognitive measures. The second objective was to examine the distribution and frequency of high scores on cognitive testing across sport classifications. As previous research has suggested, athletes involved in strategic and open-skill sports must sustain both physical and cognitive performance over extended periods, often under high-pressure and fatigue-inducing conditions, all while making effective decisions (e.g., Koch & Krenn, 2021;

Voss et al., 2010). For this reason, it is hypothesized that team sport athletes will consistently achieve the greatest proportion of high scores. The methodologies and results are presented in Chapter 3. Overall, Study1 and Study 2 seek to further refine the literature on athletes' cognitive profiles by taking a multidimensional approach to examine athletes' cognitive profiles, using neuropsychological methodologies, while examining performance differences on domain-general cognitive tasks in athletes from different sport classifications.

Chapter 2

Study 1: A Multivariate Approach to Understanding Cognitive Functioning in High-Performance Athletes

A major limitation of previous studies was the univariate approach taken to analyze cognitive functioning in athletes. This approach often overlooks the interactions and relationships between cognitive domains which are crucial to understanding athletes’ overall cognitive profile. Additionally, previous studies have predominantly assessed athletes’ cognitive performance on singular tasks, often neglecting their performance across various cognitive tasks. The main objective of Study 1 was to examine the multidimensional cognitive profiles of high-performance athletes using CNTs that assess verbal short-term (working) memory, response inhibition, attention/concentration, verbal reasoning, visuospatial working memory, deductive reasoning, episodic memory, visuospatial processing, mental rotations, working memory, spatial working memory/ planning, and visual short-term (working) memory. Further, performance was examined using traditional mean-based approaches as well as neuropsychological methods (i.e., comparison to a normative sample and multivariate base rates). Multivariate base rates were examined using athletes’ number of high scores achieved based on the ≥75th, ≥84th, and ≥91st percentiles. These high score cut-offs were selected based on previous studies employing multivariate base rates using a normative sample (e.g., Holdnack et al., 2017; Karr et al., 2016; Karr et al., 2019).

Method

Participants

This study included high-performance athletes from the Canadian Sport Institute of Ontario (CSIO), representing a wide range of sports: athletics (n = 9), basketball (n = 8), beach volleyball (n = 9), canoe/kayak (n = 3), cross-country skiing (n = 4), curling (n = 8), cycling (n = 17), diving (n = 9), figure skating (n = 3), freestyle skiing (n = 18), hockey (n = 21), indoor volleyball (n = 25), para athletics (n = 1), rowing (n = 1), rugby (n = 23), sailing (n = 4), ski moguls (n = 2), swimming (n = 3), and synchronized swimming (n = 20). No participants were actively recovering from a concussion at the time of testing. Participants with no history of concussion in the last six months were included in the final sample. It is important to note that normative data based on age and sex were only available for athletes aged 13-25. As a result, 20 individuals were excluded from the sample for falling outside this age range. Only participants who completed the full cognitive battery were included in the final analysis. The final sample consists of 188 athletes from the CSIO, with 109 females (57.8%) and 79 males (42.2%). The athletes' ages ranged from 13 to 25 years, with a mean age of 16.56 (SD = 1.95).

Materials

Cognitive tests

The Creyos cognitive battery (www.creyos.com, previously known as Cambridge Brain Sciences) is a web-based computerized neurocognitive assessment that comprises of 12 distinct cognitive tests that evaluate the following cognitive processes: verbal short-term (working) memory, response inhibition, attention/concentration, verbal reasoning, visuospatial working memory, deductive reasoning, episodic memory, visuospatial processing, mental rotations, working memory, spatial working memory/ planning, and visual short-term (working) memory. This battery has been used to assess cognitive functioning in a wide range of individuals (Owen et al., 2010; Wild et al., 2018), as well as athletes from a range of skill levels (Brewer-Deluce et al., 2017; De Waelle et al., 2021; Kamali et al., 2023). The Creyos cognitive battery has demonstrated strong test-retest reliability and convergent validity in numerous large-scale studies (Hampshire et al., 2012; Nichols et al., 2020). Below is a detailed description of each test.

Double trouble (DT)

This task is an iteration on the classic Stroop test (Stroop, 1935) that assesses participants’ ability to inhibit information. In DT, a target appears on the screen in either a red colour or blue colour. Participants are tasked to select the probe word that corresponds to the colour that the target word is drawn too. The colour mappings can either be congruent (i.e., every word correctly describes the displayed colour), incongruent (i.e., target word or the probed word are displayed in opposite colours), or double incongruent (i.e., target and probe are both displayed in colours that are opposite to what is being described). Each participant has 90 seconds to complete as many trails as they can within the specified time. A correct response is worth 1 point while an incorrect response removes 1 point from the participant's total score.

Spatial planning

Spatial planning is a task that is based on the Tower of London (Shallice, 1982), which is primarily used as a measure of spatial working memory/planning. In this task, numbered beads are placed on a tree and participants are asked to rearrange the beads in ascending numerical order. Participants are given 4-minutes to solve as many puzzles as possible. For every puzzle completed, the trial increases in difficulty each time. A trial is stopped if participants make more than twice the required number of moves required to solve the problem. For each completion of a puzzle, the participants' final score increased by 2 multiplied by the minimum number of moves required subtracted from the number of moves made.

Odd One Out

Odd One Out is a task based on reasoning problems from the Cattel Culture Fair intelligence test (Cattell, 1949). Nine groups of coloured shapes are presented in a grid format consisting of different colours, shapes and number of items present. These items define each group and are related to one another through a set of rules. Participants are asked to spot a pattern and identify the group that does not pertain to the current set of rules. Participants are given 90 seconds to solve as many problems as possible. Correct responses result in one point while an incorrect response reduced the total score by one point.

Grammatical Reasoning

Grammatical reasoning is a task that assesses verbal reasoning based on Baddeley's 3-min Grammatical Reasoning test (Baddeley, 1968). For each trial, participants are presented with two shapes on the screen with a corresponding statement. Participants are then asked to indicate if the statement correctly describes the shapes displayed. Participants are given 90 seconds to complete as many responses as possible. Correct responses result in a total score of one point while incorrect responses result in a reduction of one point.

Polygons

Polygons is a task based on the interlocking pentagons test that assesses visuospatial functioning (Folstein et al., 1975). For each trial, participants are presented with overlapping wire-framed polygons on the left side of the monitor. Participants are tasked with identifying if the shape to the right is identical to one of the two overlapping ones on the left side of the screen. Correct responses increase the difficulty of the subsequent trial (i.e., differences in overlapping polygons will be less distinct). Each participant has 90 seconds to complete as many trials as possible.

Digit span

Digit span is a verbal working memory task based on the revised Wechsler Adult Intelligence Scale (Wechsler, 1981). This task presents participants with a sequence of digits displayed one after another in the center of the monitor. Participants must repeat these digits by selecting a sequence of digits via an on-screen keyboard. Difficulty is dynamically varied as the previous tests mentioned. The test ends after three mistakes made. Individuals score is the length of the longest digit sequence recalled.

Rotations

Rotations is task designed to assess individuals' mental rotation skills. Each trial consists of two groups of coloured squares (each containing n squares) beside one another. One group is rotated by a multiple of 90 degrees. Each group is either identical or differs by position, one item at a time. Participants must indicate if the groups presented match. Correct responses increase the final score by n while subsequent trial has groups of n + 1 squares. If participants record an incorrect response, the total score decreases by n, and the next trial has groups of n – 1 squares.

Token Search

Token Search assesses participants working memory skills during search related tasks (e.g., Collins et al., 1998). This task presents participants with a set of boxes with a hidden green token in one of the boxes displayed on a grid. Participants are then asked to find the token by clicking one box at a time. Once the token is found, the token is then placed in a new box. A token will not be in a box that previously held a token, thus requiring participants to remember previous correct responses. A wrong answer occurs when a participant chooses a box that was a correct answer previously. A new trial begins when participants select a box that has not been previously used to identify a token. The trial ends after three errors and participants' maximum level is their final score.

Paired Associates

Paired Associates is a task designed to measure participants' episodic memory and is commonly used in research involving individuals with mild to severe memory impairments (e.g., Gould et al., 2005). A set of boxes will appear on the participants' monitor at random and are to open one after another to reveal an icon after they close. These icons are to be displayed sequentially in the center of the screen and athletes will then be tasked to select a box that contains that item. If participants remember all the icon-location pairs the next trial will add an additional box. If an error is made, the following trial will have one less box. The task ends after three errors. Participants' maximum number of matched pairs in their total score.

Spatial Span

Spatial Span is a visual short-term (working) memory task based on the Corsi block-tapping test. In the current task, sixteen purple blocks are displayed in a grid and a selected number of boxes turn green one at a time (900ms per green square). Participants are then asked to repeat the sequence by clicking the boxes in the same order. Once more, difficulty varies dynamically. The test ends after three errors. Participants' final score is the length of the longest successful sequence recalled.

Feature Match

Feature Match is a perceptual discrimination task in which two boxes appear on the screen, each displaying an array of abstract shapes. Participants must determine whether the arrays are identical or different and respond by clicking the appropriate button. Task difficulty adapts in real-time based on participant performance, maintaining an optimal level of challenge throughout.

Monkey (Number) Ladder

Monkey (Number) Ladder is a visuospatial working memory task in which numbered boxes briefly appear in random locations on the screen. After the numbers disappear, participants must recall the sequence by clicking the boxes in ascending numerical order. The task adapts in difficulty based on performance, with scores reflecting the average number of boxes correctly remembered.

Procedure

This study was approved by the Human Participants Review Sub-Committee of York University's Ethics Review Board. Participants provided written informed consent before completing the cognitive tests. Participants completed the cognitive assessment using a computer with an attached computer mouse either at the CSIO or on their personal time. Standardized written and pictorial instructions preceded each cognitive test. Participants reviewed the instructions and completed practice trials before the test trials. Tests were presented in a randomized sequence, and the battery took approximately 40 minutes to complete.

Statistical Analysis

Descriptive statistics for each cognitive test were calculated (e.g., mean and standard deviation) for continuous variables where applicable. Individual’s raw scores across the 12 distinct tasks were standardized into T-scores (age and sex matched) based on a normative sample of non-athletes (n ~ 5,000) that were extracted from the Creyos battery normative sample. Multivariate base rates (MVBs) were calculated using the following cut-offs: ≥75th, ≥84th, and ≥91st percentile. To assess the relationships between the number of high scores (≥=75th percentile) achieved across the cognitive tasks, the Phi coefficient was calculated. This analysis was used to examine the strength and direction of associations between high scores on different tasks, providing insights into potential shared cognitive patterns. Lastly, an Exploratory Factor Analysis (EFA) with an Oblimin rotation was conducted to examine athletes' latent cognitive profiles by examining the relationships among observed variables. This analysis explored the underlying patterns that define shared cognitive dimensions and latent constructs.

Results

The means, standard deviations, and proportions of high scores across each cognitive task are presented in Table 1. As shown, participants generally performed well in tasks assessing verbal reasoning, visuospatial working memory, and deductive reasoning at or above the 75th percentile (i.e., approximately 30% of the sample). Specifically, a greater proportion of athletes achieved high scores at or above the 75th percentile across all cut-offs, than would be expected if we assume a normal distribution (i.e., 25% at the 75th percentile, 16% at the 84th percentile, and 9% at the 91st percentile). For example, in a task assessing visuospatial working memory, 30% achieved a high score (≥75th percentile), 24% reached the ≥84th percentile, and 13% scored at or above the 91st percentile. The proportion of athletes that achieved multiple high scores on the Creyos cognitive battery at the ≥75th, ≥84th, and ≥91st percentiles are presented in Table 2.

Table 1.

Group Mean, Standard Deviation and Univariate Proportions of High Scores Achieved

Cognitive Test	Cognitive Domain	*M*	*SD*	75th Percentile	84th Percentile	91st Percentile
Digit Span	Verbal Short-Term (Working) Memory	48.48	11.25	20%	9%	8%
Double Trouble	Response Inhibition	47.51	11.49	24%	11%	5%
Feature Match	Attention/Concentration	46.74	10.50	19%	10%	7%
Grammatical Reasoning	Verbal Reasoning	50.52	10.19	30%	15%	10%
Number (Monkey) Ladder	Visuospatial Working Memory	49.83	12.07	30%	24%	13%
Odd One Out	Deductive Reasoning	51.08	9.66	29%	19%	8%
Paired Associate	Episodic Memory	47.26	10.37	15%	9%	5%
Polygons	Visuospatial Processing	45.57	8.63	12%	5%	2%
Rotations	Mental Rotations	50.24	12.16	28%	18%	13%
Token Search	Working Memory	47.30	12.97	18%	5%	5%
Spatial Planning	Spatial Working Memory/ Planning	49.25	8.24	17%	11%	6%
Spatial Span	Visual Short-Term (Working) Memory	51.24	9.64	21%	15%	7%

Note: Percentages represent the proportion of high scores achieved at or above the listed percentile rank.

Table 2.
Multivariate Base Rates of High Scores Achieved

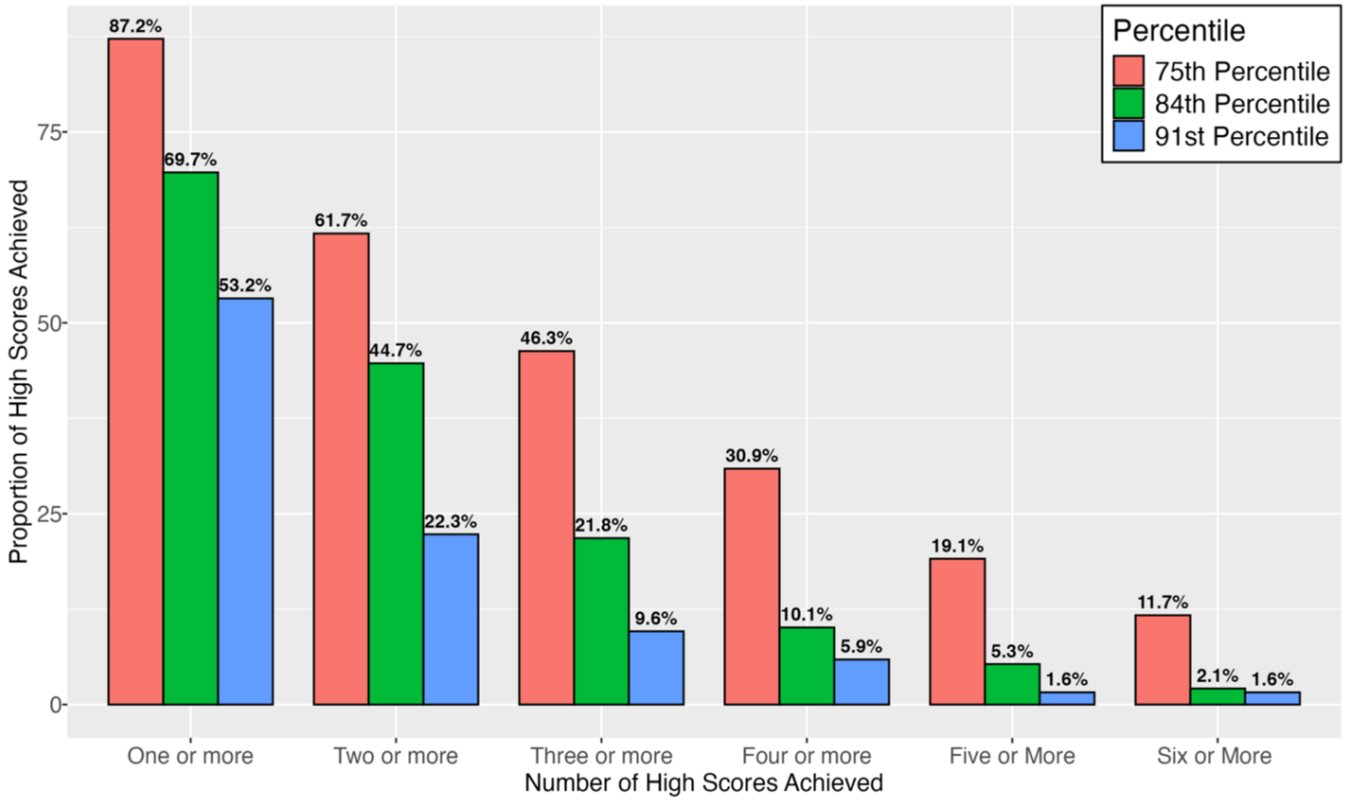
Number of High Scores	75th Percentile	84th Percentile	91st Percentile
No high scores	12.8	30.3	46.8
1 or more	87.2	69.7	53.2
2 or more	61.7	44.7	22.3
3 or more	46.3	21.8	9.6
4 or more	30.9	10.1	5.9
5 or more	19.1	5.3	1.6
6 or more	11.7	2.1	1.6
7 or more	5.9	2.1	1.1
8 or more	3.7	0.5	-
9 or more	1.1	-	-
10 or more	0.5	-	-
11 or more	0.5	-	-
12 high scores	-	-	-

Note: All values represent cumulative percentages except for the row titled “No high scores”, which provides the proportion of scores that did not fall above the high score cutoffs. Only participants without missing data were included in the base rate calculation.

Across all cutoffs (i.e., percentile ranks), it was relatively common for athletes to achieve at least one high score. As expected, the proportion of high scores decreased as the cutoff increased. For example, 87.2% of athletes achieved a high score at or above the 75th percentile, 69.7% achieved at least one high score at or above the 84th percentile, and 53.2% reached the 91st percentile or higher. When considering the achievement of three or more high scores, 46.3% reached at least the 75th percentile, 21.8% achieved this at or above the 84th percentile, and 9.6% did so at or above the 91st percentile. This trend illustrates that while athletes frequently achieved a single high score across the three cutoffs, the occurrence of multiple high scores across the cognitive tasks decreases. However, while the overall occurrence remains notable, its magnitude compared to a non-athlete sample is unclear (i.e., we do not know how it compares to a normative sample). This trend continued as the number of high scores increased. Please see Figure 1 to visualize the distribution of high scores.

Figure 1.

Visualizing Multivariate Base Rates of High Scores: Creyos Cognitive Battery

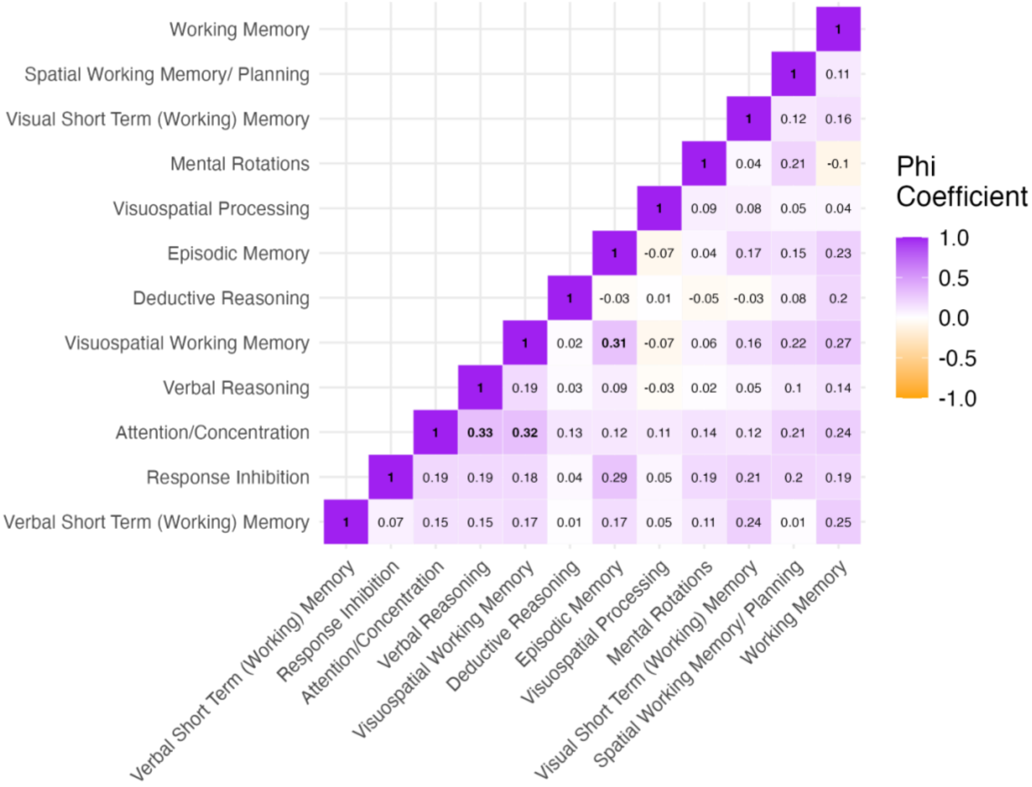


Note: All values are rounded to the nearest tenth.

To explore the relationships between high scores across cognitive tests (i.e., examining patterns in high scores), Phi coefficients were calculated for scores at or above the 75th percentile (high score = 1, low score = 0). There was a moderate positive association between Paired Associate (i.e., episodic memory) and Monkey (Number) Ladder (i.e., visuospatial working memory) ($\Phi = 0.31$, $p < .001$), a moderate positive association between Feature Match (i.e., attention/concentration) and Monkey (Number) Ladder ($\Phi = 0.32$, $p < .001$), as well as a moderate positive association between Feature Match and Grammatical Reasoning (i.e., verbal reasoning; Φ = 0.33, p < .001). These correlations indicate that higher performance on one test is associated with higher performance on other related cognitive domains. To visualize the correlations between all cognitive tests of interest, please see Figure 2.

Figure 2.

Associations Between High-Scores Achieved on the Creyos Cognitive Battery



Finally, an EFA was conducted to identify latent cognitive profiles based on performance across various observed cognitive tests. To assess the suitability of the sample for EFA, a Kaiser-Meyer-Olkin (KMO) test was conducted to evaluate sample adequacy (Kaiser, 1970), while Bartlett's Test of Sphericity was used to determine whether item correlations were appropriate for EFA (Bartlett, 1954). Assumptions were met for both diagnostic tests employed. The following requirements were followed to run the current EFA model: (1) no cross loadings among items (i.e., items load highly on multiple factors); (2) factor loadings must be more than 0.40 (Matsunaga, 2010). Items that do not fulfill these requirements are to be removed from the model, and the EFA is repeated until an ideal model fit is identified. It is important to note that although factors are recommended to include at least three items (e.g., *Syarifah Farradinna et al., 2023*), we felt that it was appropriate to include a factor with only two items given the alignment with a theoretical cognitive construct (i.e., working memory), strong factor loadings as well as adequate variability explained.

In total, 5 items did not meet the requirements of the EFA model. All 5 items had factor loadings that were below 0.40. As a result, the EFA model comprises of two factors that collectively account for 36.3% of the variance in the patterns of item relationships. Factor 1 explained 19.3% of the variance, with a sum of squares (SS) loading of 1.34, while Factor 2 accounted for 17.0% of the variance, with an SS loading of 1.19. To enhance clarity, each factor is labeled with a descriptive name (Kline, 2016; Ponnam et al., 2014). The first factor, *attention/executive function* was made up of the following items: Double Trouble (response inhibition), Polygons (visual spatial processing/reasoning), Token Search (working memory), Feature Match (attention/concentration), Grammatical Reasoning (verbal reasoning). The second factor, *short-term (working) memory,* was made up of the following items: Digit Span [verbal short-term (working) memory], and Spatial Span [visual short-term (working) memory]. Table 3 demonstrates the final two factor model.

Table 3.

Creyos Cognitive Battery's Final Items and Two Factor Structure

	Loading
Factor 1: *Attention/Executive Function*	
Double Trouble	0.52
Polygons	0.47
Token Search	0.48
Feature Match	0.64
Grammatical Reasoning	0.44
Factor 2: *Short-term (Working) Memory*	
Digit Span	0.89
Spatial Span	0.60

Seven items from the CBS cognitive battery were identified, with loadings ranging from 0.47-0.89, by (1) attention/executive function—5 items with loading ranging from 0.47 to 0.64, (2) short-term (working) memory—2 items with loading ranging from 0.60 to 0.89. These loadings demonstrate strong parsimony among the latent factors, effectively capturing the underlying structure of the data.

Discussion

This study examined multidimensional cognitive profiles of high-performance athletes using a CNT that assessed 12 cognitive domains. Existing research on domain-general cognitive functioning has primarily relied on mean-based analyses and univariate approaches, focusing on individual cognitive domains, without accounting for the dynamic interplay among cognitive domains. This leaves a gap in our understanding of how different cognitive abilities interact to shape athletes' overall cognitive profile. By adopting a multidimensional approach, this study provides a more comprehensive perspective on cognitive functioning in high-performance athletes.

The present study found that athletes exhibited superior performance on tasks assessing visuospatial working memory, verbal reasoning, and deductive reasoning. Notably, a higher-than-expected proportion of athletes scored at or above the 75th, 84th, and 91st percentile cut-offs, exceeding what would typically be anticipated under a normal distribution (i.e., 25% at the 75th percentile, 16% at the 84th, and 9% at the 91st). While within a normal distribution, it is expected that 25%, 16%, and 9% of individuals to score at or above these respective cutoffs, a larger proportion of athletes in our sample achieved scores at these cutoffs across multiple tasks (i.e., specifically in deductive reasoning and visuospatial working memory). This pattern may indicate that athletes exhibit superior cognitive abilities compared to what is expected of the general population. These findings align with prior research suggesting that athletes outperform non-athletes in domains such as working memory, visuospatial skills, and broad domains of EF. For instance, Verburgh et al. (2014) found that high-performance soccer players outperformed amateur players in tasks relating to inhibition and sustained attention. Likewise, Alves et al. (2013) found that high-performance volleyball players had superior performance on executive control and visuospatial tasks. Similarly, Wang et al. (2015) demonstrated superior visuospatial performance in badminton players relative to non-athletic controls. Arguably, these cognitive domains play a role in effective decision-making and problem-solving that are often seen among athletes in fast-paced sports (Romeas et al., 2016; Qiu et al., 2018; Vu et al., 2022). However, the patterns in proportions of high scores in this study also highlight the need to evaluate the use of non-athlete reference values when interpreting athlete performance. Nevertheless, the results of the current study suggest that athletes may not only demonstrate superior cognitive performance in traditional domains like EF but also reasoning abilities that are crucial to problem-solving and decision-making in complex sporting environments.

By applying neuropsychological principles (i.e., comparing scores to a normative population and calculating multivariate base rates), the current study demonstrated that while many athletes excelled in at least one task assessing a specific cognitive domain, the proportion of high scores decreased when examining high performance across multiple tasks. This pattern may not be atypical when considering the cognitive skills required of specific athletes based on the demands of their sport. For instance, when comparing the distribution and frequency of high scores obtained across various cognitive tests, there appears to be a lack of uniformity. While some athletes may excel in particular domains, such as visuospatial working memory or deductive reasoning, their overall cognitive profiles do not consistently reflect superior performance across all tasks. It is possible that these sport-specific demands may result in performance differences on domain-general cognitive tasks, rather than indicating a universally superior cognitive ability across all domains assessed. Prior research has demonstrated that performance differences on cognitive tasks may be, in part, due to sport-specific demands. For example, athletes engaged in fast-paced, dynamic sports (e.g., hockey, volleyball) have been shown to demonstrate superior performance on tasks assessing visual processing, attention, and visuospatial skills (Memmert, 2009; Vona et al., 2024; Williams et al., 2011). In contrast, athletes from more self-paced and static sports, such as golf or archery, exhibit superior performance in tasks involving inhibitory control, working memory, and information processing (Li et al., 2024; Li, Zhao, et al., 2024; Rehfeld et al., 2018). Therefore, understanding how these sport-specific demands influence cognitive performance is crucial when examining athletes' overall cognitive profiles. This notion refers to the concept of task specificity, which refers to the idea that athletes may excel in particular tasks related to their sport, but their superior performance does not extend to other domains outside of their expertise (Voss et al., 2010). For this reason, further exploration of multivariate base rates in athletes using CNTs is needed to assess the consistency of high scores across cognitive domains, identify potential ceiling effects, and examine how task-specific demands shape cognitive performance patterns across athletes from different sport classifications.

The relationship between episodic memory, visuospatial working memory, attention/concentration, and verbal reasoning highlight the interconnectedness of cognitive abilities in athletes, aligning with research on integrated cognitive processes in sport performance (Vestberg et al., 2017; Voss et al., 2010). These observed relationships suggest that athletes may possess a heightened ability to encode and retrieve information, which is enhanced by a strong spatial processing capacity. This aligns with theories that visuospatial cues aid in tracking movement patterns and anticipating opponents' actions, which are crucial for in-game adaptation and success (Furley & Memmert, 2010). The relationship between attention/concentration and visuospatial working memory supports the notion that attentional control is crucial for strong working memory performance (Engle, 2002). Athletes with high attentional abilities may better allocate cognitive resources to encode and manipulate spatial information, essential for tracking teammates, processing dynamic cues, and maintaining situational awareness (Faubert, 2013). More so, athletes who excel in attentional control often exhibit advanced reasoning skills, enabling them to make swift tactical adjustments and engage in strategic decision-making during competition (Vestberg et al., 2012). Furthermore, analyzing the relationships between cognitive domains and superior performance reinforces the importance of a holistic approach to understanding cognition rather than examining abilities in isolation. This perspective enables sport practitioners to identify co-occurring cognitive strengths among high-performance athletes, helping to recognize cognitive profiles that align with specific sport types, playing styles, and positional demands (Walton et al., 2018).

Additionally, two distinct latent factors underlying cognitive performance on the Creyos cognitive battery were identified: attention/executive function and short-term (working) memory. Prior research on the relationship between tasks on the Creyos cognitive battery in a healthy population identified three distinct factors: Short-term memory, reasoning, and verbal abilities (Hampshire et al., 2012). The current study's findings are similar, though with some notable differences in the factor structures between high-performance athletes and a normative sample. The current study identified two factors: attention/executive function and short-term (working) memory. In contrast, prior research using a normative sample shows a more distinct separation of cognitive domains, suggesting that cognitive tasks in the general population are more compartmentalized. This difference may reflect the cognitive demands of high-performance athletes, which require the integration of multiple cognitive processes, whereas non-athletes demonstrate a broader, more isolated factor structure. Furthermore, the findings of the current study indicate that the factor reflecting athletes' attention and executive function encompasses tasks that align with previous research, which has identified associations between sport expertise and superior performance in tasks assessing visuospatial processing, decision-making, and attention (Berry et al., 2008; González-Víllora et al., 2015; Nakata et al., 2010). Also, in line with previous research, working memory has been identified as a key component of in-game decision making (Furley & Memmert, 2010). Unlike studies that use working memory as a broad EF proxy (e.g., Koch & Krenn, 2021; Huijgen et al., 2015; Vestberg et al., 2017; Wu et al., 2024), our findings reveal how these two domains of working memory (i.e., verbal and visual) contribute differently to athletes multimodal working memory, with task-specific demands influencing outcomes.

While the current study identified several cognitive domains in which athletes demonstrate superior performance, the absence of a comparison group limits our ability to make statements about whether these patterns of high scores reflect a cognitive profile specific to high-performance athletes or simply reflect variability within an athlete population. In Study 2, we aim to address this limitation by specifically exploring performance differences on domain-general cognitive tasks among athletes from different sport types.

Chapter 3

Study 2: Cognitive Functioning Across Sport Classifications: Insights from High-Performance Athletes

Study 2 expands on Study 1 by exploring performance differences in domain-general cognitive tasks across athletes from various sports. While Study 1 used a multidimensional approach to identify cognitive strengths in high-performance athletes through CNTs, Study 2 extends this multidimensional approach to examine cognitive performance differences based on athletes' sport classification.

A key limitation of Study 1 was the absence of a control group, making it difficult to determine whether the elevated scores (i.e., multivariate base rates) observed in athletes reflect distinct cognitive patterns or fall within normal population variability. Additionally, Study 1 did not compare athletes across different sports, limiting the ability to assess whether specific cognitive strengths are unique to certain sports or shared across athletic disciplines. To address this, Study 2 compared the domain-general cognitive performance of high-performance athletes across three sport classifications: team, speed/strength, and precision/skill-dependent. We examined these cognitive profiles in athletes using the sport classification system proposed by McKay et al. (2022). These classifications were formed by considering sport-specific physiological demands, tactical components, and skill requirements in both practice and competition. This classification system was chosen for its clear, defined criteria, offering a more precise approach compared to other commonly used classification systems (e.g., open vs. closed sports). Athletes competing in open-skill, strategic, and/or team sports must sustain both cognitive and physical performance across extended periods of time in both training and competition. These sporting environments require athletes to face fast-paced and unpredictable situations, requiring them to make rapid decisions under pressure and fatigue—underscoring the elevated cognitive and physical demands associated with these sport classifications. For this reason, it is hypothesized that team sport athletes would outperform athletes in other sport classifications on domain-general cognitive tasks. Furthermore, we examined the distribution and frequency of high scores across these sport classifications, predicting that team sport athletes would achieve the greatest proportion of high scores.

Method

Participants

The sample employed in Study 2 is the same as the one employed in Study 1 (See Chapter 2 for more details). It is important to note that normative data based on age and sex were available for athletes aged 13-25. As a result, 20 individuals were excluded from the sample for falling outside this age range. Participants included in the final sample had no history of concussion in the past six months and were not actively recovering from one at the time of testing. Only those who completed the full cognitive battery were included in the analysis. The final sample consists of 188 athletes from the CSIO, with 109 females (57.8%) and 79 males (42.2%). The athletes' ages ranged from 13 to 25 years, with a mean age of 16.56 (SD = 1.95).

Sport Classification

This study included high-performance athletes from 19 different sports that were organized into three distinct classifications based on employing the sport classification system proposed by McKay et al. (2022). The three classifications included in the current study are team, speed/strength, and precision/skill-dependent sports. Team sports are dynamic and strategic, demanding athletes to process a constant influx of unpredictable information from teammates, opponents, and sport-specific elements (e.g., hockey puck, soccer ball). Athletes in these sports also need to exhibit exceptional endurance, agility, and strength to perform effectively. Speed and strength sports require athletes to generate maximum force in a brief period. These sports prioritize strength and velocity over precision during high-intensity movements (e.g., cycling, swimming). Precision/skill-dependent sports are characterized by the execution of highly coordinated, pre-planned routines that demand technical accuracy, artistic expression, and refined motor control. Athletes in these sports must demonstrate exceptional flexibility, balance, strength, and power to execute precise movements.

Materials

Cognitive Tests

Athletes' overall cognitive functioning was assessed using twelve tasks from the Creyos cognitive battery (www.creyos.com; i.e., Cambridge Brain Sciences), a validated neuropsychological battery used to assess domain-general cognition. The cognitive battery evaluated cognitive processes in the following areas: verbal short-term (working) memory, response inhibition, attention/concentration, verbal reasoning, visuospatial working memory, deductive reasoning, episodic memory, visuospatial processing, mental rotations, working memory, spatial working memory/ planning, and visual short-term (working) memory. This battery has been used to assess cognition in a variety of individuals (Owen et al., 2010; Wild et al., 2018), as well as in athletes from various ages and classifications of sport-expertise (Brewer-Deluce et al., 2017; De Waelle et al., 2021; Kamali et al., 2023). The Creyos cognitive battery has demonstrated strong test-retest reliability and convergent validity in numerous large-scale studies (Hampshire et al., 2012). A comprehensive description of each test can be found in Appendix A.

Procedure

Before completing the cognitive assessment, all participants provided written informed consent. Testing was conducted on a computer with a standard mouse, either at the CSIO or at a location of their choosing. Each cognitive task was preceded by standardized written and pictorial instructions, which participants reviewed before completing a practice trial to familiarize themselves with the task demands. The test battery, presented in a randomized sequence, took approximately 40 minutes to complete. This study received ethical approval from the Human Participants Review Sub-Committee of York University's Ethics Review Board.

Statistical Analysis

Descriptive analyses were conducted for each cognitive test, including mean and standard deviation for continuous variables where relevant. To examine whether belonging to a particular sport group (i.e., team, speed/strength, or precision/skill-dependent) was associated with greater cognitive performance (using raw scores), multiple-linear regression analysis was conducted. Regression analysis was conducted to enable group comparisons while also providing effect sizes, directional relationships, and coefficients that quantify how the outcome changes relative to a reference group. Team sport was chosen as the reference group because of the a priori hypothesis that team-based athletes would outperform athletes from other sports. All models met assumptions of linearity, normality, and homoscedasticity of errors. No evidence of multicollinearity was observed among the predictors. To facilitate comparisons across the 12 cognitive tasks, raw scores were then converted into T-scores. These standardized scores were adjusted for age and sex using a normative dataset of approximately 5,000 non-athletes, ensuring a meaningful baseline for interpreting athlete performance across cognitive tests. To better understand the distribution of high scores achieved, multivariate base rates (MVBs) were calculated using the following percentile cut-offs: ≥75th, ≥84th, and ≥91st. Chi-square analyses were conducted to determine if there are significant differences in the distribution of high scores across the three sport classifications, allowing for an inferential examination of whether the proportions of athletes achieving high scores varies by sport type. Some comparisons between high score thresholds could not be conducted due to an insufficient number of observations meeting the assumptions of the chi-square test (i.e., expected cell counts). As more athletes obtained high scores at or above the 75th percentile, we were able to run a greater number of comparisons between high-score thresholds. In contrast, fewer individuals reached the 91st percentile, which limited the number of comparisons that could be performed at that level. Each threshold reflects the number of high scores achieved across the entire cognitive test (e.g., one or more, two or more, etc.). Six thresholds (i.e., one or more, two or more, three or more, four or more, five or more, six or more high scores) were included in the model assessing high scores at or above the 75th percentile, four thresholds (i.e., one or more, two or more, three or more, four or more high scores) in the model for high scores at or above the 84th percentile, and three thresholds (i.e., one or more, two or more, three or more high scores) in the model for high scores at or above the 91st percentile.

Results

Examining the Influence of Sport Classification on Cognitive Performance

Demographic information and sport information for participants is presented in Table 4. Multiple-linear regression models were conducted across twelve cognitive tests using athletes raw scores to examine the association between sport classification on cognitive functioning among high-performance athletes. To account for multiple comparisons, p-values were adjusted using the False Discovery Rate correction to control the risk of false positives. Specifically, when assessing the Spatial Span task, which measures visual short-term (working) memory, sport classification explained a significant proportion of the variance in the model ($R^2 = .04$, $F(2, 185) = 4.63$, $p < .001$). The precision/skill-dependent sport group ($\beta = -0.57$, $t(185) = -2.69$, $p < .001$) and the speed/strength sport group ($\beta = -0.53$, $t(185) = -2.29$, $p < .029$) had significantly lower scores compared to individuals in team sports. Similarly, when assessing the Double Trouble task, assessing response inhibition, sport classification explained a small but significant portion of the variance ($R^2 = .03$, $F(2, 185) = 3.36$, $p < .003$). The precision/skill-dependent sport group ($\beta = -7.01$, $t(185) = -2.59$, $p < .001$) had significantly lower scores compared to individuals in team sports. When analyzing the Monkey (Number) Ladder task, which evaluates visuospatial working memory, sport classification showed a significant effect as well ($R^2 = .04$, $F(2, 185) = 2.70$, $p < .001$). The precision/skill-dependent sport group ($\beta = -1.02$, $t(185) = -2.81$, $p < .001$) and the speed/strength sport group had significantly lower scores compared to individuals in team sports ($\beta = -0.85$, $t(185) = -2.29$, $p < .039$). Finally, the Token Search task, which assesses general working memory, approached significance ($R^2 = .03$, $F(2, 185) = 2.84$, $p = .006$). The precision/skill-dependent sport group ($\beta = -0.77$, $t(185) = -2.31$, $p < .002$) had significantly lower scores compared to individuals in team sports. For a more comprehensive summary of the results, please refer to Table 5.

Table 4.

Sample Characteristics by Sport Classification

Sport Category	Sport	Sample Size			Age
		All	Female	Male	Mean ± SD
Precision	Diving	9	6	3	15.11±1.69
	Figure Skating	3	2	1	17.33±4.93
	Sailing	4	2	2	18.75±2.36
	Ski Moguls	2	1	1	14.5±2.12
	Artistic Swimming	20	20	0	14.35±1.49
	Freestyle Ski	18	0	18	15.44±0.85
	Total	56			
Speed/Strength	Athletics	9	6	3	19.33±1.00
	Canoe/Kayak	3	1	2	18.00±1.00
	Cross Country Skiing	4	1	3	20.50±2.64
	Cycling	17	6	11	17.5±2.31
	Para Athletics	1	1	0	18.0±NA
	Swimming	3	2	1	17.00±1.00
	Rowing	1	0	1	20.00±NA
	Total	38			
Team	Basketball	8	7	1	15.36±1.17
	Beach Volleyball	9	7	2	16.77±0.83
	Curling	8	5	3	18.75±1.03
	Hockey	21	21	1	16.50±0.51
	Rugby	23	12	11	15.87±1.01
	Indoor Volleyball	25	10	15	16.40±0.77
	Total	94			

Table 5.

Cognitive Differences Based on Sport Classification

Model	Predictor	Mean	SD	*β*	*SE*	95% CI	*t*	*p*
Model 1: Spatial Span	Intercept (Team)	6.24	1.47	6.24	0.13	[6.00, 6.48]	48.58	**< .001**
	Precision	5.68	0.92	-0.57	0.21	[−0.99, −0.15]	-2.69	**< .001**
	Speed/Strength	5.71	1.04	-0.53	0.24	[-1.00, -0.07]	-2.23	**< .002**
Model 2: Number (Monkey) Ladder	Intercept (Team)	8.59	2.63	8.59	0.22	[8.15, 9.03]	38.659	**< .001**
	Precision	7.57	1.33	-1.02	0.36	[-1.74, -0.30]	-2.81	**< .005**
	Speed/Strength	7.74	1.78	-0.85	0.41	[-1.67, -0.04]	-2.07	**< .039**
Model 3: Double Trouble	Intercept (Team)	28.90	15.30	28.90	1.6	[25.58, 32.11]	17.44	**< .001**
	Precision	21.80	15.90	-7.01	2.7	[-12.35, -1.67]	-2.59	**< .010**
	Speed/Strength	26.60	18.00	-2.21	3.08	[-8.29, 3.86]	-0.72	.472
Model 4: Token Search	Intercept (Team)	8.57	2.09	8.57	0.19	[8.18, 8.96]	43.50	**< .001**
	Precision	7.80	1.58	-0.77	0.32	[-1.40, -0.13]	-2.28	**< .018**
	Speed/Strength	8.34	1.92	-0.23	0.36	[-0.95, 0.49]	-0.63	.529

Note: *p*-values were adjusted using the False Discovery Rate correction to control the risk of false positives.

Sport Classification and the Proportion of High Scores on a Cognitive Battery

The proportions of high scores on the Creyos cognitive battery, classified by the ≥75th, ≥84th, and ≥91st percentiles, are displayed in Table 6. These proportions were classified in two ways: (1) proportion of athletes who achieved a high score at a specific percentile rank and (2) the proportion of athletes who attained multiple high scores across the percentile rank.

Table 6.

Multivariate Base Rates of High Scores Achieved

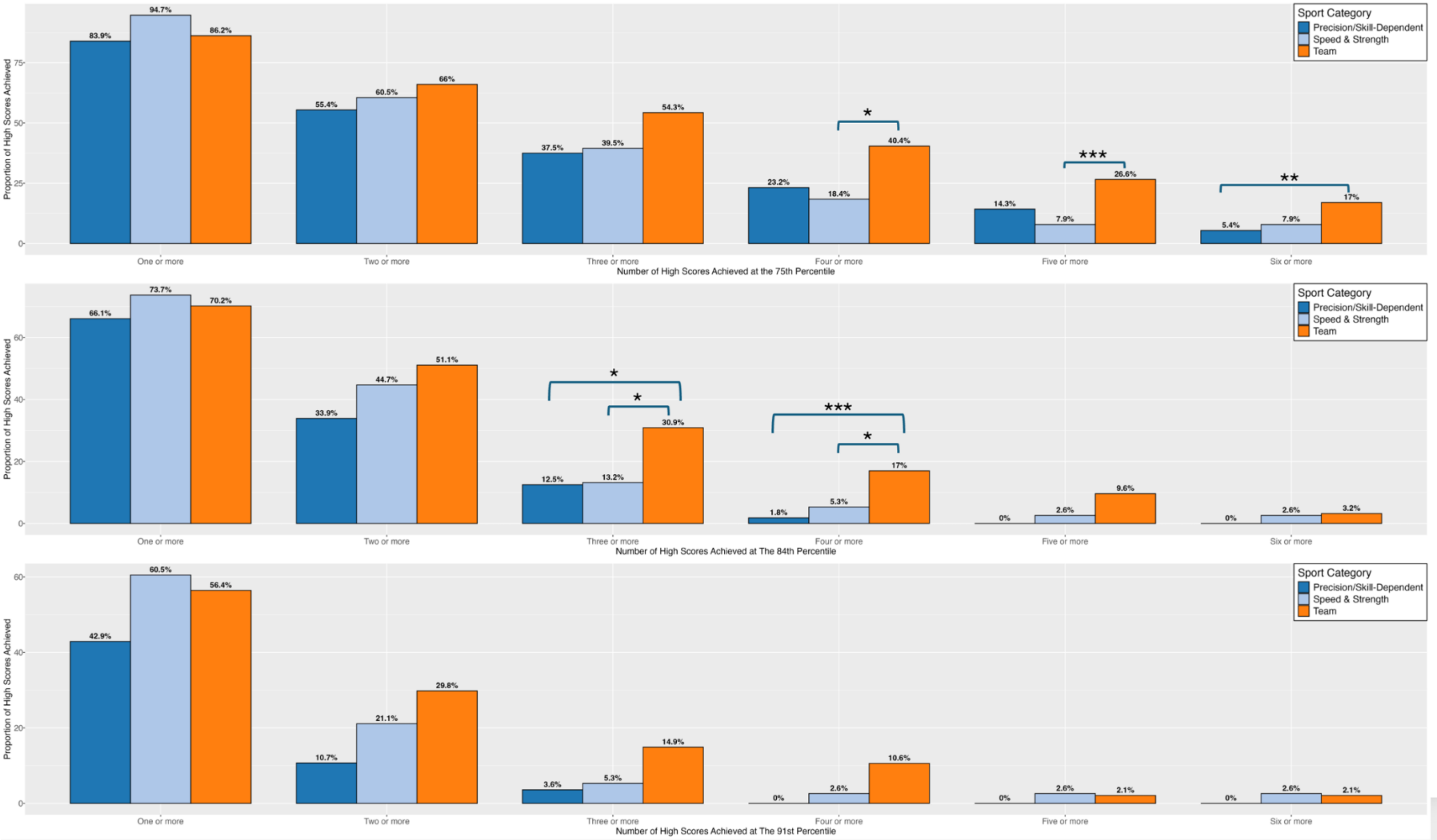
Number of High Scores	75th Percentile			84th Percentile			91st Percentile		
	PS	SS	T	PS	SS	T	PS	SS	T
No high scores	16.1	5.3	13.8	33.9	26.3	29.8	57.1	39.5	43.6
1 or more	83.9	94.7	86.2	66.1	73.7	70.2	42.9	60.5	56.4
2 or more	55.4	60.5	66.0	33.9	44.7	51.1	10.7	21.1	29.8
3 or more	37.5	39.5	54.3	12.5	13.2	30.9	3.6	5.3	14.9
4 or more	23.2	18.4	40.4	1.8	5.3	17.0	-	2.6	10.6
5 or more	14.3	7.9	26.6	-	2.6	9.6	-	2.6	2.1
6 or more	5.4	7.9	17	-	2.6	3.2	-	2.6	2.1
7 or more	1.8	5.3	8.5	-	2.6	3.2	-	2.6	1.1
8 or more	-	5.3	5.3	-	-	1.1	-	-	-
9 or more	-	2.6	1.1	-	-	-	-	-	-
10 or more	-	-	1.1	-	-	-	-	-	-
11 or more	-	-	1.1	-	-	-	-	-	-
12 high scores	-	-	-	-	-	-	-	-	-

Note: Sport classifications are presented in the following order: Precision/skill dependent (PS) /speed-strength (SS) /team (T). All values represent cumulative percentages, except for the 'No high scores' row, which indicates the percentage of participants who did not exceed any high score cutoffs. The base rate calculation includes only participants with complete data.

Across all percentile ranks (75th, 84th, 91st), athletes from every sport classification consistently achieved at least one high score. However, as the percentile rank increased, the proportion of athletes achieving high scores decreased across all classifications of sport (see Table 3). For instance, at the 75th percentile, between 83.9%–94.7% of athletes obtained at least one high score, relative to only 42.9%–60.5% of athletes at the 91st percentile. When looking at the proportion of high scores achieved by sport type, speed/strength athletes had the highest proportion of athletes achieving at least one high score across all percentile thresholds (94.7%-60.5%), followed by team (86.2%-56.4%) and precision/skill-dependent athletes (83.9 %-42.9%). The values inside the brackets indicate the range of athletes achieving at least one high score from the 75th to the 91st percentile. However, as the cutoff for the number of high scores achieved increased, team sport athletes had the greatest proportion of high scores achieved across all percentile ranks. For instance, at the 75th percentile for 4 or more high scores, team sport athletes (40.4%) consistently achieved a greater proportion of high scores than speed/strength (18.4%) and precision/skill-dependent athletes (23.2%). When analyzing the proportion of 4 or more high scores at the 91st percentile, athletes from team sports had a greater proportion of high scores (10.6%) relative to speed/strength (2.6%) and precision/skill-dependent sports (0%). Please see Figure 3 to better visualize this relationship.

Figure 3.

Proportion of High Scores Achieved by Sport Classification



Note: Asterisks indicate statistically significant differences between sport categories based on Chi-square tests:* p < .05, ** p < .01, *** p < .001.

A series of chi-square tests of independence were performed to examine the number of high scores achieved between different sport classifications. First, when comparing the number of high scores achieved across the three sport classifications at or above the 75th percentile, there is a significant difference between the expected and observed number of high scores achieved, $\chi 2(10, N = 188) = 20.60$, $p < .002$, $V = 0.11$. Post-hoc Bonferroni-adjusted comparisons revealed statistically significant differences in the number of high scores achieved, with team sports outperforming speed/strength sports at the four or more ($p < .012$), and five or more ($p < .001$) high scores cut off, as well as outperforming precision/skill-dependent sports at the six or more ($p < .004$) high scores cutoff. A similar pattern emerged at the 84th percentile, $\chi 2(6, N = 188) = 19.16$, $p < .001$, $V = 0.15$. Post-hoc Bonferroni-adjusted comparisons revealed statistically significant differences in the number of high scores achieved, with team sports outperforming speed/strength at the three or more ($p < .002$) and four or more ($p < .039$) high score cutoff as well as outperforming precision/skill-dependent sports at the three or more ($p < .015$) and four or more ($p < .001$) high score cutoff. However, when looking at the number of high scores achieved across the three sport classifications at or above the 91st percentile, there is no significant difference between the expected and observed number of high scores achieved, $\chi 2(6, N = 188) = 8.69$, $p = .006$, $V = 0.13$.

Discussion

The purpose of Study 2 was to examine performance differences on domain-general cognitive tasks among athletes from different classifications of sports. We hypothesized that team sport athletes would demonstrate superior cognitive performance compared to those in speed/strength and precision/skill-dependent sports. Additionally, we expected team sport athletes to achieve the highest proportion of high scores across various thresholds. The results of the current study extend the findings from Study 1. More specifically, Study 1 examined foundational cognitive profiles for high-performance athletes from a variety of sport backgrounds and Study 2 examined differences in cognitive performance in athletes based on sport type.

Expanding on the initial hypothesis, our results indicate that team sport athletes exhibited superior performance in visual short-term (working) memory, response inhibition, visuospatial working memory, and working memory compared to those in speed/strength and precision/skill-dependent sports. When examining sport-specific differences through the lens of the cognitive skill transfer hypothesis, previous research has suggested that the superior cognitive functioning observed in team sport athletes may have a greater influence on domain-general cognitive skills compared to athletes in precision/skill-dependent and speed/strength sports (Bianco et al., 2017; Krenn et al., 2018; Voss et al., 2010). According to this hypothesis, cognitive demands of team sports, where athletes frequently engage in interactions with teammates and opponents in dynamic, unpredictable environments, may contribute to superior EF abilities (Alves et al., 2013; Heppe et al., 2016). In our study, we observed that team-based athletes also demonstrated superior performance in tasks assessing working memory and visuospatial working memory when compared to athletes from the other sport classifications. As team sports consistently achieved greater cognitive performance across various tasks compared to athletes in speed/strength and precision/skill-dependent sports, it is vital to understand the demands behind these different types of sports. Individuals from speed/strength and precision/skill-dependent sports take part in activities that require fewer externally driven cognitive demands during competition (e.g., pre-planned routine, sprinting), which perhaps may explain part of the differences observed in cognitive performance in our study. However, it is also possible that athletes self-select into their sport based on pre-existing cognitive strengths or preferences that then may develop based on training and competition demands. Given the cross-sectional nature of the data, the directionality of this relationship cannot be determined.

Further, team sport athletes achieved a greater proportion of high scores relative to other sport classifications across two of the three percentile cutoffs examined (i.e., 75th, and 84th). While speed/strength athletes had the highest proportion of athletes that achieved at least one high score, team sport athletes had the highest proportion of high scores as the threshold (i.e., number of high scores achieved) increased. These findings are consistent with previous research demonstrating that athletes in open-skill or externally-paced sports (e.g., team sports) tend to demonstrate superior cognitive functioning—particularly in areas such as attention, EF, and decision-making—compared to those in closed-skill sports (Holfelder et al., 2020; Koch & Krenn, 2021; Krenn et al., 2018; Meng et al., 2019; Rahimi et al., 2022; Voss et al., 2010; Yu & Liu, 2020). These findings may support the notion that athletes in speed/strength and precision/skill-dependent sports rely more on physical skills and less on higher-order cognitive functions (Holfelder et al., 2020; Voss et al., 2010). In contrast, the multifaceted demands of team sports—such as rapid decision-making, strategic planning, and real-time adaptability—may foster superior domain-general cognitive functioning (Bianco et al., 2017; Kida et al., 2005; Krenn et al., 2018; Voss et al., 2010). This aligns with existing research suggesting that the dynamic and unpredictable nature of team, strategic, and open sports, which demand continuous adaptation, quick decision-making, and strategic thinking, may contribute to superior EF (Alves et al., 2013; De Waelle et al., 2021; Heppe et al., 2016; Rahimi et al., 2022). Furthermore, previous research suggests that the cognitive demands specific to a particular sport may not only influence athletes' univariate performance on singular cognitive tasks, but more importantly their performance across numerous tasks. By examining athletes’ multivariate base rates according to their classification of sport, we can gain insights into the unique patterns in the distribution and frequency of high scores achieved across different sports.

Chapter 4

General Discussion

The overarching goal of the current thesis was to contribute to our understanding of cognitive performance in high-performance athletes by applying a multidimensional approach that utilizes neuropsychological methodologies. To do so, we examined cognitive profiles of high-performance athletes by assessing their performance across 12 tasks on a CNT. As previous researchers have predominantly focused on assessing athletes EF using univariate approaches, Study 1 sought to compare athletes multidimensional cognitive profiles using neuropsychological principles. Study 2 extended this approach and applied it to examine performance differences in domain-general cognitive tasks between different classifications of sport. As previous studies often employ broad classifications of sport to compare athletes' cognitive performance, Study 2 employed a classification framework that emphasizes athletes sport-specific physiological demands, tactical components, and skill requirements in both practice and competition.

In Study 1, athletes demonstrated strong performance across multiple domain-general cognitive tasks (e.g., visuospatial working memory, verbal reasoning, and deductive reasoning). Notably, most athletes excelled in at least one out of the twelve tasks administered. However, fewer athletes consistently achieved high scores across multiple tasks, possibly indicating a task-specific expertise rather than broad cognitive superiority. Further, two latent factors, attention/executive function and short-term (working) memory were identified, reflecting the underlying structure of cognitive performance in athletes. Moreover, observed correlations in tasks assessing episodic memory, visuospatial working memory, attention/concentration, and verbal reasoning highlight potential multidimensional relationships within athletes' cognitive profiles. These patterns suggest that certain abilities may cluster together, offering a foundation for future research assessing athletes' cognitive performance. Study 2 expanded on this multidimensional approach by examining sport-specific differences in cognitive functioning, identifying how the unique demands of different sport classifications contribute to superior cognitive functioning in athletes. Athletes from a team sport background had significantly greater cognitive performance on tasks assessing visual short-term (working) memory, response inhibition, visuospatial working memory, and working memory compared to those in speed/strength and precision/skill-dependent sports. In addition, team sport athletes had the highest proportion of high scores as the threshold for the number of high scores increased.

While the current thesis found evidence of superior cognitive performance in high-performance athletes as well as significant differences across different classifications of sport, previous research has reported mixed findings on the relationship between athletic participation and cognitive functioning (Ben-Shachar & Berger, 2024; Heppe et al., 2016; Jansen & Lehmann, 2013; Wang et al., 2018). These results may be influenced by factors such as the specific aspect of cognition measured, the assessment method used (e.g., CNT vs. paper-and-pencil neuropsychological tests), and the type of group examined (e.g., high-performance athletes, para-athletes, or single vs. mixed sport athletes; Burris et al., 2019; Chiu et al., 2017; Di Russo et al., 2010; Krenn et al., 2018; Meng et al., 2019). This highlights the importance of methodology when assessing domain-general cognitive functioning. As the current study demonstrated strong cognitive functioning in our sample of athletes when assessed using a CNT, researchers employing different modalities of assessing cognitive functioning have yielded different results (e.g., Karr et al., 2018; Vestberg et al., 2017). The inconsistency in findings regarding sport type and cognitive functioning may be due to variations in how sports are classified. Studies using the open-closed skill classification have shown that athletes from open skill sports tend to perform better on cognitive tasks; however, findings from more detailed classification systems tend to vary depending on the domains assessed, how those domains are measured, as well as the classification system used. (Holfelder et al., 2020; Mann et al., 2007; Takahashi & Grove, 2023; Voss et al., 2010). For instance, some studies suggest that engaging in team sports enhances performance in tasks related to processing speed and EF, while others have found that athletes from speed/strength sports outperform on cognitive flexibility tasks (Voss et al., 2010; McKay et al., 2022). Despite these complexities, the findings of this thesis emphasize the importance of adopting a multidimensional approach when examining domain-general cognitive performance in high-performance athletes. Also, by employing a more nuanced sport classification framework, Study 2 effectively captures the diverse cognitive demands across various sport types, providing a clearer and more accurate comparison of athletes' cognitive performance.

The current thesis is among the first to look at the distribution and frequency of high scores achieved to assess domain-general cognitive functioning in high-performance athletes, offering a deeper understanding of cognitive profiles across a range of cognitive tasks. This approach expands on previous research in both clinical and healthy populations (Brooks et al., 2010; Karr et al., 2016) by revealing that it is common for athletes, regardless of sport classification, to achieve at least one high score (i.e., 75%ile or above) on the cognitive battery. These findings align with previous studies involving both normative and clinical samples, which have suggested that isolated high scores in specific cognitive domains are relatively common, even in the absence of superior performance across broader, domain-general tasks (Karr et al., 2016, 2018). Although we did not include a comparison group in the current study, patterns of cognitive performance observed in Table 1 offer compelling descriptive insights. Assuming a normal distribution, we would expect approximately 25%, 16%, and 9% of individuals to score at or above the 75th, 84th, and 91st percentiles, respectively. When looking at athletes' cognitive performance in Study 1, nearly 30% surpassed the 75th percentile on Grammatical Reasoning (i.e., verbal reasoning), Odd One Out (deductive reasoning), and Monkey (Number) Ladder (i.e., visuospatial working memory). Furthermore, over 18% exceeded the 84th percentile and 13% exceeded the 91st percentile on Rotations (i.e., mental rotations), while 24% exceeded the 84th percentile and 13% exceeded the 91st percentile on Monkey (Number) Ladder. These findings further underscore the importance of understanding patterns of performance at the individual task level, as this may reflect unique strengths and sport-specific advantages in particular domains of cognition rather than suggesting a generalized cognitive superiority (Karr et al., 2019). Such patterns may indicate that athletes from similar sport classifications consistently achieve high scores on specific cognitive tasks, reflecting the relevance of those domains to sport-specific skills. However, interpreting athletes’ performance solely at the individual task level limits our understanding of how cognitive domains interact with one another. For this reason, a more integrated approach better captures the interconnected nature of cognitive functioning and how these relationships align with the multifaceted demands of different sports. For this reason, when interpreting the distribution and frequency of multiple high scores being achieved, as the percentile rank increased, fewer athletes maintained high scores across additional tasks (i.e., had more than one test score at that percentile rank). The patterns observed in this thesis align with those found in previous research examining the multivariate base rates of high scores in a normative sample who completed the D-KEFS (i.e., measure of EF). Karr et al. (2019) found that high scores, though less frequent at higher thresholds, were present across various age groups and populations. Without a direct comparison group (e.g., non-athlete controls), it is not possible to make broad statements about this performance pattern. However, if this pattern were similar to healthy controls, then perhaps this could provide evidence of task-specific expertise. In other words, if both athletes and non-athletes demonstrate similar proportions of cognitive performance, this may suggest that task performance is not driven by a superior cognitive ability but rather experience or familiarity with the cognitive demands of a particular task. As athletes frequently engage in consistent cognitive demands during training and competition, this may result in specialized cognitive skills which may manifest as task-specific expertise. For this reason, comparisons to a normative sample are necessary to uncover if athlete's domain-general cognitive performance reflects unique task-specific advantages or merely reflect broader cognitive patterns in a normative population. While many participants excelled in one task, fewer scored highly across multiple tasks. As such, our results further align with prior studies on skill transfer limitations (Furley & Wood, 2016), which suggests that athletes may excel in certain cognitive tasks but not universally across all domains. Further, a notable finding in this thesis is the sustained high performance of team sport athletes as the percentile thresholds increased (i.e., 75th – 91st percentile), which may suggest that the dynamic, fast-paced, and unpredictable nature of team sports could play a role in cognitive performance (Alves et al., 2013; Heppe et al., 2016). Team sports appear to require a broad set of cognitive skills that extend beyond physical training that can potentially influence cognitive performance in ways that may not be seen in other sport classifications.

Understanding the cognitive advantages observed in team sport athletes can inform talent identification and scouting efforts. Integrating cognitive profiling into these programs may help uncover athletes who have not yet reached peak physical performance but exhibit superior cognitive abilities in domains critical to their sport that may be predictive of future sporting success (Vestberg et al., 2012; Voss et al., 2010). Understanding the specific cognitive advantages among athletes in team sports may help the overall team composition to optimize communication strategies as well as select specific athletes that may be best suited for specific positional demands. For instance, athletes who score high in cognitive flexibility have been demonstrated to adapt to new tactical systems and take on new responsibilities within their sport (Chen et al., 2024). Also, Schumacher et al. (2018) identified significant position-related differences in sustained attention and reaction time tasks in high-performance soccer players, with midfielders showing faster visual reactions and defenders excelling in figural sustained attention. These findings highlight the role of how specialized cognitive profiling can be used to employ positional specific protocols among athletes from team sport classifications, to enhance players' abilities to adapt to dynamic game situations. Incorporating these insights into coaching strategies can further promote a more individualized approach, where cognitive performance is valued alongside both physical and technical sport abilities. Overall, by broadening our understanding of how sport-specific characteristics shape cognitive functioning, this thesis contributes to the growing body of literature that recognizes the complex interplay between physical training, technical knowledge, and cognitive performance in high-performance athletes.

Implications

The current thesis explored the multidimensional cognitive profiles of high-performance athletes, providing a foundation for future research to investigate how these cognitive traits may translate into sport-specific performance outcomes. Although there are preliminary studies that have demonstrated how superior cognitive functioning can predict sport-related success, more work is needed (Hirao & Masaki, 2018; Romeas et al., 2016). To fully understand how cognition influences athletic performance, it is crucial to explore the interaction between multiple cognitive domains. For example, how do cognitive abilities such as visuospatial working memory and attentional control work together to enhance performance in fast-paced, strategic sports like soccer or hockey? Investigating these interactions in a more ecologically valid setting could offer deeper insights into the specific cognitive mechanisms that underpin success in different sports. Understanding these unique cognitive profiles among athletes from different classifications of sport can highlight the potential of cognitive profiling in scouting, talent identification, and personalized training beyond physical conditioning. Further, by asking more sport specific questions, this enables researchers to further refine athlete identification practices to highlight specific athletes who fit the cognitive profile that is crucial for success in a particular sport. Although limited, studies have demonstrated the potential predictive validity of cognitive performance in athletes' long-term success, with working memory and processing speed task performance correlating with higher athletic performance levels (Huijgen et al., 2015; Walton et al., 2018). These findings emphasize the need to consider athletes' cognitive functioning alongside their physical attributes. By recognizing the cognitive demands specific to each sport, coaches can design training regimens that target both mental and physical performance. This holistic approach allows for a more tailored development plan, enhancing athletes' overall abilities and better preparing them for the unique challenges of their sport.

Limitations

As the current thesis advances our understanding of cognitive functioning in high-performance athletes, there are several limitations to be addressed. The primary limitation of this thesis is the lack of population-level information for multivariate base rates in Study 1. Not having normative multivariate base rate information limited the ability to make meaningful comparisons between our sample of high-performance athletes and a normative (non-athlete) population. This limited the ability to determine if these high scores in athletes reflect a distinct cognitive profile or are within the normal variability seen among a normative population. Additionally, another limitation is the restrictive age range employed in the current study. This was in part to available normative data available in our sample. This limitation hinders the development of more comprehensive cognitive profiles that span a wider age range, limiting the generalizability of the findings to other stages of athletes' cognitive development. Furthermore, this data was cross-sectional and thus it is not possible to decipher the potential influence of self-selection (e.g., an athlete with specific cognitive strengths self-selecting into a sport) or sport development (i.e., training) on cognitive performance. Future longitudinal studies, examining the development of cognitive skills in athletes across the lifespan, would help shed light on this critical interplay. Another limitation is the uneven distribution of sex across sport classifications, with some sports being predominantly represented by one sex (e.g., females in artistic swimming). This imbalance may limit the generalizability of findings across sport classifications. Future research should strive for a more balanced representation to better examine potential interactions between sex and sport type in shaping cognitive performance. Lastly, the absence of real-time monitoring for fatigue-related disengagement posed a limitation, as some athletes completed the CNT independently due to isolation requirements during the COVID-19 pandemic. This lack of oversight may have led to decreased effort on later tasks, potentially influencing the performance outcomes.

Future Directions

While the current studies employed domain-general cognitive tasks to construct multidimensional cognitive profiles of high-performance athletes, further research is needed to establish how these profiles compare to those of a normative population. By conducting multivariate base rate analyses of cognitive performance in non-athletes, future studies could determine whether the high scores observed in athletes reflect distinct cognitive profiles or if they fall within the expected range of variability seen in the general population. This comparison would provide greater insight into the unique cognitive characteristics of high-performance athletes. Furthermore, as the current study employed a sport classification framework that is based on tactical, physiological, and skill demands, offering an improved approach, cognitive domains can still vary within each classification of sport (e.g., cognitive load differences among hockey players vs. volleyball players). To overcome such pitfalls, a more individualized approach to understanding how sport specific effects is necessary. However, we recognize the challenges involved in such research, including access to specific sports of sufficient sample sizes. While the current study adopted a group-level approach to examining athletes' cognition—particularly through the use of multivariate base rates—future research is encouraged to take an individual-level approach, as this can better capture within-group variability while offering personalized insights into how cognitive functioning supports sport-specific performance. Lastly, future research is encouraged to employ more ecologically valid assessments of cognitive functioning alongside a CNT to encompass a more holistic approach to understanding athletes cognitive functioning. In doing so, researchers can test both the expert performance approach and the broad transfer hypothesis to help determine the cause of potential cognitive advantages in high-performance athletes.

Conclusions

The current set of studies advances our understanding of high-performance athletes' domain-general cognitive abilities in several ways. Firstly, this study enhanced our knowledge of domain-specific cognitive functioning in athletes by employing neuropsychological methodologies to construct comprehensive, multidimensional cognitive profiles. Secondly, it provided valuable insights into how team sport athletes exhibit superior cognitive functioning when assessed using domain-general cognitive tasks, relative to athletes in other sport classifications. These approaches underscore the importance of adopting a holistic perspective when examining cognitive profiles, emphasizing how the variability and interrelationships among cognitive domains can inform athlete identification, development, and sport-specific performance outcomes. Finally, the study highlights the need for future research to take a more individualized approach in assessing cognitive functioning in high-performance athletes, considering the unique demands of each sport, the type of cognitive assessments employed, and the specific athlete groups being studied. By addressing these factors, the current thesis aims to lay a foundation for future research, guiding the use of cognitive profiling to inform talent identification and development strategies for high-performance athletes.

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Appendix A

Double trouble (DT)

This task is an iteration on the classic Stroop test (Stroop, 1935) that assesses participants' ability to inhibit information. In DT, a target appears on the screen in either a red colour or blue colour. Participants are tasked to select the probe word that corresponds to the colour that the target word Is drawn too. The colour mappings can either be congruent (i.e., every word correctly describes the displayed colour), incongruent (i.e., target word or the probed word are displayed in opposite colours), or double incongruent (i.e., target and probe are both displayed in colours that are opposite to what is being described). Each participant has 90 seconds to complete as many trails as they can within the specified time. A correct response is worth 1 point while an incorrect response removes 1 point from the participant's total score.

Spatial planning

Spatial planning is a task that is based on the Tower of London (Shallice, 1982), which is primarily used as a measure of spatial working memory/planning. In this task, numbered beads are placed on a tree and participants are asked to rearrange the beads in ascending numerical order. Participants are given 4-minutes to solve as many puzzles as possible. For every puzzle completed, the trial increases in difficulty each time. A trial is stopped if participants make more than twice the required number of moves required to solve the problem. For each completion of a puzzle, the participants' final score increased by 2 times the difference between the minimum number of moves required and the number of moves made.

Odd One Out

Odd One Out is a task based on reasoning problems from the Cattel Culture Fair intelligence test (Cattell, 1949). Nine groups of coloured shapes are presented in a grid format consisting of different colours, shapes and number of items present. These items define each group and are related to one another through a set of rules. Participants are asked to spot a pattern and identify the group that does not pertain to the current set of rules. Participants are given 90 seconds to solve as many problems as possible. Correct responses result in one point while an incorrect response reduced the total score by one point.

Grammatical Reasoning

Grammatical reasoning is a task that assesses verbal reasoning based on Baddeley's 3-min Grammatical Reasoning test (Baddeley, 1968). For each trial, participants are presented with two shapes on the screen with a corresponding statement. Participants are then asked to indicate if the statement correctly describes the shapes displayed. Participants are given 90 seconds to complete as many responses as possible. Correct responses result in a total score of one point while incorrect responses result in a reduction of one point.

Polygons

Polygons is a task based on the interlocking pentagons test that assesses visuospatial functioning (Folstein et al., 1975). For each trial, participants are presented with overlapping wire-framed polygons on the left side of the monitor. Participants are tasked with identifying if the shape to the right is identical to one of the two overlapping ones on the left side of the screen. Correct responses increase the difficulty of the subsequent trial (i.e., differences in overlapping polygons will be less distinct). Each participant has 90 seconds to complete as many trials as possible.

Digit span

Digit span is a verbal working memory task based on the revised Wechsler Adult Intelligence Scale (Wechsler, 1981). This task presents participants with a sequence of digits displayed one after another in the center of the monitor. Participants must repeat these digits by selecting a sequence of digits via an on-screen keyboard. Difficulty is dynamically varied as the previous tests mentioned. The test ends after three mistakes made. Individuals score is the length of the longest digit sequence recalled.

Rotations

Rotations is task designed to assess individuals' mental rotation skills. Each trial consists of two groups of coloured squares (each containing n squares) beside one another. One group is rotated by a multiple of 90 degrees. Each group is either identical or differs by position, one item at a time. Participants must indicate if the groups presented match. Correct responses increase the final score by n while subsequent trial has groups of n + 1 squares. If participants record an incorrect response, the total score decreases by n, and the next trial has groups of n – 1 squares.

Token Search

Token Search assesses participants working memory skills during search related tasks (e.g., Collins et al., 1998). This task presents participants with a set of boxes with a hidden green token in one of the boxes displayed on a grid. Participants are then asked to find the token by clicking one box at a time. Once the token is found, the token is then placed in a new box. A token will not be in a box that previously held a token, thus requiring participants to remember previous correct responses. A wrong answer occurs when a participant chooses a box that was a correct answer previously. A new trial begins when participants select a box that has not been previously used to identify a token. The trial ends after three errors and participants' maximum level are their final score.

Paired Associates

Paired Associates is a task designed to measure participants' episodic memory and is commonly used in research involving individuals with mild to severe memory impairments (e.g., Gould et al., 2005). A set of boxes will appear on the participants' monitor at random and are to open one after another to reveal an icon after they close. These icons are to be displayed sequentially in the center of the screen and athletes will then be tasked to select a box that contains that item. If participants remember all the icon-location pairs the next trial will add an additional box. If an error is made, the following trial will have one less box. The task ends after three errors. Participants' maximum number of matched pairs in their total score.

Spatial Span

Spatial Span is a visual short-term (working) memory task based on the Corsi block-tapping test. In the current task, sixteen purple blocks are displayed in a grid and a selected number of boxes turn green one at a time (900ms per green square). Participants are then asked to repeat the sequence by clicking the boxes in the same order. Once more, difficulty varies dynamically. The test ends after three errors. Participants' final score is the length of the longest successful sequence recalled.

Feature Match

Feature Match is a perceptual discrimination task in which two boxes appear on the screen, each displaying an array of abstract shapes. Participants must determine whether the arrays are identical or different and respond by clicking the appropriate button. Task difficulty adapts in real-time based on participant performance, maintaining an optimal level of challenge throughout.

Monkey (Number) Ladder

Monkey (Number) Ladder is a visuospatial working memory task in which numbered boxes briefly appear in random locations on the screen. After the numbers disappear, participants must recall the sequence by clicking the boxes in ascending numerical order. The task adapts in difficulty based on performance, with scores reflecting the average number of boxes correctly remembered.