The Sport & Concussion Research on Executive Systems (SCoRES) Study:

A Quantitative and Qualitative Examination of Executive Function, Sport and Physical Activity in Young Adults

by

Madeline Doucette
Bachelor of Science, University of Northern British Columbia, 2019

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

MASTER OF SCIENCE

in the Department of Psychology

I acknowledge with respect the Lekwungen peoples on whose traditional territory the university stands and the Songhees, Esquimalt and WSÁNEĆ peoples whose historical relationships with the land continue to this day.

Supervisory Page

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Supervisory Committee

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Abstract

Introduction: The cognitive benefits of physical activity and sport on executive function are of interest to researchers, especially considering the subsequent interventions that could be implemented. However, researchers frequently use different approaches to conceptualize and measure executive function, often using only a few computerized tasks. My Master's thesis, therefore, aims to investigate the associations between executive function and physical activity and sport through two different studies to obtain a robust evaluation of executive function: 1) A quantitative study examining physical activity, sport and concussion history in university students and their effect on executive function, and 2) A qualitative study exploring the executive functions engaged during a game from elite university athletes' experiences.

Methods: *Quantitative Study.* Canadian university students (n=247) completed an online study with nine computerized executive function tasks and a behavioural self-report of executive function, as well as questions assessing weekly physical activity, athletic status, and concussion history. Structural equation modelling and linear regression were conducted to predict executive function based on age, sex, physical activity, athletic status and concussion history. *Qualitative study*. Canadian university athletes (n=19) participated in semi-structured interviews via Zoom to determine the executive functions engaged during a game. Thematic analysis was used to analyze the interview transcripts.

Results: *Quantitative Study.* The three-factor model of executive function had an overall good fit: $\chi2 = 66.38$, $df = 51$, $p = 0.07$, CFI = 0.95, TLI = 0.93, RMSEA = 0.04 [90% CI: 0.00–0.06], SRMR = 0.05. No direct relationship was found between the factors and age, physical activity, concussion history, or athletic status. Sex was significantly related to inhibition, $b = 0.52$, $p = 0.02$, such that males had greater inhibition. Physical activity ($b = 0.09$, $p < .01$), concussion history ($b = 3.29$, $p < .05$) and athletic status ($b = -4.01$, $p < .05$) were found to be significant predictors in the regression predicting self-reported executive functioning. *Qualitative study*. Three themes were generated: 1) Engaging in pre-play or pre-game planning, organization and decision making, 2) Engaging in mid-play problem solving and purposive action and 3) Engaging in post-play or post-game information processing, emotional control and effective performance.

Conclusions: The quantitative study found that physical activity, athletic status and concussion history were predictive of subjective but not objective executive function. The qualitative study determined that athletes engage many executive functions that are dependent on the timing of both the play and the game (pre-, mid- or post-). Real-life behavioural manifestations of executive functioning are more challenging to assess and measure but may be better predicted by and relate to life factors such as physical activity and sport participation. The results of my thesis provide support for future research to utilize and develop more unique and ecologically valid methods of measuring EF in the field of physical activity and sport.

Keywords: executive function, neuropsychology, physical activity, concussion, sport

Table of Contents

List of Tables

List of Figures

Acknowledgments

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Chapter 1: Literature Review

Despite how often executive function (EF) is studied, the concept remains ill-defined with many theoretical frameworks and definitions [e.g., Miyake et al.'s (2000) three latent factor approach; Lezak et al.'s (2004) definition; Jurado & Roselli's (2007) definition; etc.]. Broadly, EF is considered a higher-order cognitive function that produces goal-directed behaviours in novel situations (Duggan & Garcia-Barrera, 2015). In the past, there has been considerable debate on whether EF is a unitary, singular construct or if it consists of diverse separable functions (Karr et al., 2018). Development in EF research through interdisciplinary fields, including experimental psychology, neuropsychology and neuroscience, has determined that there are separate unique functions that can be isolated, such as inhibition, set-shifting, verbal fluency, organization, cognitive flexibility and conflict monitoring, that, while discrete, are interconnected within the frontal lobes (Aron, 2008; Garcia-Barrera, 2019; Packwood et al., 2011). However, with this influx of unique and separate EFs, researchers have realized the lack of clarity in the conceptualization of EF with an abundance of proposed components of EF currently existing. Packwood and colleagues (2011) identified 68 subcomponents of EF and 98 unique EF tasks through an initial literature review. After accounting for semantic and psychometric overlap between different EFs, they reduced the 68 EF subcomponents to 18. Still, 18 components of EF are substantial and may be indicative of task-specific expressions of executive functioning rather than separate EFs (Packwood et al., 2011). Interestingly, the most commonly referred to EF terms were planning, inhibition, fluency, working memory and set-shifting, which is similar to

Miyake et al.'s (2000) proposed three factor model with the addition of fluency and planning.

Miyake and colleagues' (2000) seminal paper determined that the three latent factors of EF: shifting, updating, and inhibition are distinguishable but moderately correlated. Shifting is thought to be the ability to change or shift perspective, attention or responses (Diamond, 2006; Miyake et al., 2000). Updating, or updating of working memory, is the ability to hold and then manipulate information in one's mind (Diamond, 2006; Miyake et al., 2000). Lastly, inhibition is the ability to suppress inappropriate responses and to stay focused and ignore distractions (Miyake et al., 2000). These three latent factors are considered lower-order EF processes that work together to produce higher-order EFs, such as decision-making, problem-solving, and planning (Gilbert & Burgess, 2008). Thus, researchers now conceptualize EF as having both unity and diversity with lower-order processes interacting and providing the input needed to create higher-order EF processes as shown below in Figure 1.

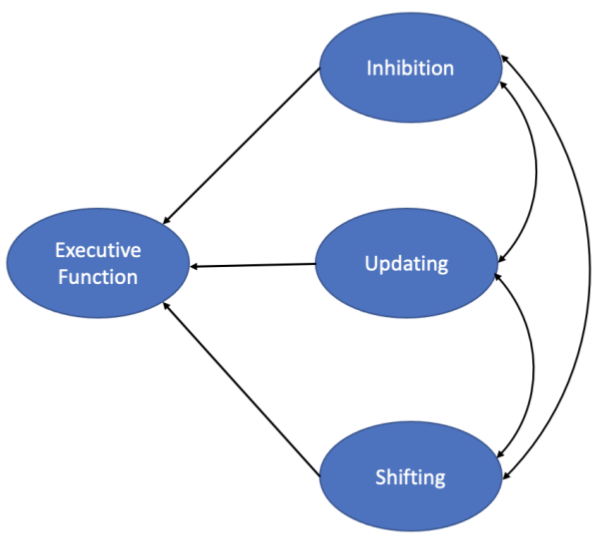

Figure 1. Schematic of the lower-order EF processes, inhibition, updating, and shifting interacting to create a common, higher-order executive function.

Researchers first assumed that EF develops throughout childhood and adolescence but remains relatively fixed once a person reaches adulthood. However, current research has shown that EF may be malleable to specific environmental, cultural and lifestyle factors such as exercise and stress (Finch & Obradović, 2018; Vrinceanu et al., 2018). For example, exercise and physical activity improve executive functioning, which has important implications for interventions and training in clinical settings to help those struggling with EF deficits (Barenberg et al., 2011). Overall, EF is a complex cognitive process that is malleable to external factors and is involved in many daily activities such as planning, organization and decision making.

Differentiating between EF and Other Psychological Constructs

Psychological constructs such as intelligence, working memory, and self-regulation seem conceptually similar to EF. For example, EF and intelligence are similar concepts used to explain complex and higher-order cognitive functioning. Intelligence has no single definition, like EF, but is often thought to be a higher-order cognitive process involving abstract reasoning, problem solving, and knowledge acquirement that has a general factor or *g* that supports performance on cognitive tasks (Spearman, 1961; Duggan & Garcia-Barrera, 2015). Early work with patients with frontal lobe damage supports the first differentiation between EF and intelligence. The intellectual capacity of these frontal lobe patients was still relatively intact, but their executive functioning was markedly decreased. Further, Duggan and Garcia-Barrera (2015) propose that while EF and intelligence have conceptual overlap and draw from similar cognitive resources, EF is employed when the cognitive demands are novel, while intelligence is employed when the cognitive demands are complex. Thus, while alike, there are significant differences between EF and intelligence that require distinct conceptualizations.

Similarly, experimental psychologists may solely study working memory as its own construct thought to be a combination of short-term memory and controlled attention (Cowan, 1998), whereas neuropsychologists (e.g., Miyake et al., 2000) tend to include updating working memory as a component of EF. Working memory is defined in the cognitive neuroscience field as " an emergent property… involving both active maintenance of task-relevant information, and rapid learning of arbitrary associations" (Hazy et al., 2006, p.106). Other researchers state that EF and working memory work in tandem, with EF manipulating (or updating) the working memory buffer (Carpenter et al., 2000). McCabe and colleagues (2010) investigated differences between working memory tasks and executive functioning tasks only to find a strong positive correlation between the two (r = .97) which, accounting for measurement error, implies they are the same construct. Thus, these authors proposed that working memory and EF share an underlying executive attention component (McCabe et al., 2010). Contrastingly, Lehto (1996) previously examined three higher-order EF tasks to determine if they are dependent on working memory and found only one (the Wisconsin Card Sorting Task) was significantly related to working memory capacity. The findings suggested that there is no underlying central executive that has been previously proposed but instead, there may be several executive control functions (Lehto, 1996). Therefore, the updating of working memory may be conceptualized differently depending on the field of research, but it is generally accepted to be associated with executive functioning.

Another psychological construct that can be conceptually similar to EF is self-regulation. Self-regulation is defined as "self-generated thoughts, feelings, and actions that are planned and cyclically adapted to the attainment of personal goals" (Zimmerman, 2000, p.14). Considering Packwood and colleagues (2011) identified impulsivity, controlling actions, and self-monitoring as subcomponents of EF, it can be challenging to differentiate between EF and self-regulation. However, Hofmann, Schmeichel and Baddeley (2012) argue that EF promotes self-regulation by supporting "self-regulatory goal pursuits" (p. 175). Similarly, Nigg (2017) proposes that self-regulation and EF are distinct because EF is employed in situations other than when self-regulation is needed. However, EF helps account for the deliberate cognitive actions of self-regulation. Other researchers have proposed that EF is engaged for self-regulation during emotionally neutral cognitive tasks (Bailey & Jones, 2019). Self-regulation appears, thus, to be an outcome of complex executive functioning processes.

Neural Correlates of EF

The neural correlates of EF were first explored in patients with frontal lobe damage. These studies spearheaded the investigation of executive functioning in the brain as patients with frontal lesions demonstrated difficulties in self-control and attentional shifting (Jurado & Roselli, 2007). Patients with frontal damage experiencing difficulties with planning, organization, abstract reasoning, problem-solving and decision-making were diagnosed with 'dysexecutive syndrome' (Baddeley & Wilson, 1988). Further evidence of the frontal lobes' role in EF comes from neuroimaging studies.

There are three critical neural circuits involved in EF processes that originate in the frontal lobe and project to the basal ganglia and thalamus (Alvarez & Emory, 2006; Royall et al., 2002). The first circuit is the dorsolateral (DL) prefrontal circuit, which consists of Broadman's Areas (BA) 8 – 12, 46 and 47, and the blood supply comes from the middle cerebral artery (Royall et al., 2002). The DL prefrontal circuit begins with the corticofugal pathways that project to the DL caudate nucleus and then connect to the DL portion of the globus pallidus and the rostral substantia nigra reticulata. It then continues to the parvocellular region of the medial dorsal and ventral anterior thalamic nuclei. Thalamic projections to the frontal DL convexity close the circuit (Royall et al., 2002). This circuit is implicated in many functions, including planning, shifting, verbal and spatial working memory (Alvarez & Emory, 2006).

The second circuit is the lateral orbitofrontal circuit which corresponds to BA 10 – 15 and 47. The anterior cerebral artery and the middle cerebral artery vascularly supply this circuit (Royall et al., 2002). This circuit consists of cortical projections that terminate on the ventromedial caudate nucleus and continue to the dorsomedial aspect of the internal globus pallidus and the rostromedial portion of the substantia nigra reticulata. It continues to the magnocellular region of the medial dorsal and ventral anterior thalamic nuclei and then back to the lateral orbitofrontal region. The orbitofrontal circuit is implicated in social behaviours such as inhibiting inappropriate responses or behaviours and suppressing or delaying immediate gratification (Royall et al., 2002).

The last circuit involves the frontolimbic cortex, including the anterior cingulate cortex (BA 9 – 13, 24, 25 and 32). The anterior striatum cerebral artery vascularly supplies this circuit (Royal et al., 2002). This circuit connects to the ventral striatum and continues to the ventral pallidum and rostrodorsal substantia nigra, then to the medial dorsal thalamic nucleus and terminates again at the anterior cingulate. This circuit is essential for monitoring behaviour, emotional control, interpreting emotions and error correction (Royall et al., 2002). These three circuits highlight that EF processes are distributed throughout the integrity of the whole brain but are concentrated in the frontal lobes, specifically in the prefrontal cortex.

Developmental Trajectory of EF

While the development of EF is not entirely linear, it does begin to develop in infancy and continues until around young adulthood. As previously mentioned, EF is supported by higher-order association cortices, including the prefrontal cortex, which is among the slowest to develop (Gogtay et al., 2004). Thus, EF has a lengthened developmental trajectory from birth to early childhood. Further, Garon and colleagues (2008) describe a common executive component that is a precursor to the initial development of working memory, followed by inhibition and shifting. Longitudinal studies provide early evidence regarding the development of EF. For example, Diamond (1985) tested infants (who could reach for a hidden object) bi-weekly for delayed-memory searches. Piaget's object permanence task was used where a toy was shown to an infant and then hidden in a well (A) with a brief delay, and then the infant is allowed to reach for the toy. When the hiding of the toy changes to well B, infants often reach back to well A, even though they have seen the hiding performed. As infants age from 7.5 months to 12 months, their performance and ability to correctly choose well B with greater delay periods increases (Diamond, 1985).

As one enters early childhood, critical developmental changes occur that contribute to the sophistication of EF. Cognitive shifting has been found to develop quite quickly over childhood. In children, the Dimensional Change Card Sort (DCCS; Doebel & Zelazo, 2015) task is often used to assess shifting and is very similar to the Wisconsin card sorting task, but with two dimensions: shape and colour. Zelazo and colleagues

(1996) found that three and four-year-old children could not switch dimensions when asked and perseverated on the first dimension while five-year-old children could switch dimensions. Similarly, working memory seems to show a linear increase in performance during childhood (Gathercole et al., 2004). These findings are consistent with Magar and colleagues (2010), who found evidence in support of linear EF development with both updating (n-back task; Cohen et al., 1997) and switching (number-letter switching task; Rogers & Monsell, 1995), improving between ages 11 and 17. However, some findings also support nonlinear development of EF, including findings that seventeen-year-olds score significantly higher than both eighteen and nineteen-year-olds on concept formation in the D-KEFS Letter Fluency and Sorting Tests (Taylor et al., 2013; Delis et al., 2001). Interestingly, individual differences in EF tend to be stable through preschool and middle childhood, with childhood EF scores predicting EF performance in adolescence (Friedman et al., 2011) and up to 40 years later (Casey et al., 2011).

As the frontal cortex continues to mature, higher-order EF emerges and is refined until early adulthood. While much research has focused on EF in infancy and childhood, less research has been devoted to understanding the development of EF in adolescence and young adulthood. Though, researchers have investigated the developmental trajectory of Miyake et al.'s (2000) model of three latent factors in a younger population (ages 7 – 21). They found that working memory continued to develop until twenty-one years old, shifting continued to develop until fifteen years old, but no latent factor could be derived for inhibition (Huizinga et al., 2006). The wide age range (7 – 21) of the study may partly explain why Huizinga and colleagues (2016) could not extract the third factor which aligns with previous research finding support for either a unidimensional or bifactor model of EF in children and adolescents (Karr et al., 2018). Task-specific Stop-Signal inhibition and Flanker inhibition developed until fifteen years old (Huizinga et al., 2006). Further, Romine and Reynolds (2005) found that higher-order EF such as strategy generation and planning continue to develop between 17 and 22 years old.

Finally, as adults begin to age, they may experience a deficit in their executive functioning; up to 40% of the ageing population experiences some impairment of EF (e.g., decision making; Denburg et al., 2007). So, executing functioning seems to develop at different rates both linearly and nonlinearly throughout infancy, childhood, and young adulthood. Then, it tends to plateau until it declines in older adulthood.

Measuring EF

Due to the elusive and complex nature of EF, it can be measured through various means, including neuroimaging, computerized tasks, and self-report measures. However, each method of measuring EF has different strengths and weaknesses. Often measures of EF are based on tasks that historically assess frontal lobe function (Jurado & Roselli, 2007). Further, the validity of these tests is only based on their sensitivity to damage to the frontal lobe, and the particular component of EF that is being measured in the task is often not specified (Miyake et al., 2000).

Clinically, EF is most commonly assessed using neuropsychological assessment. Two common examples of test batteries of EF include the Delis-Kaplan Executive Function System (D-KEFS; Delis et al., 2001) and the Cambridge Neuropsychological Test Automated Battery (CANTAB; Huppert et al., 1995). The D-KEFS (Delis et al., 2001) has tests such as Design Fluency Test, Trail Making Test (measures set-shifting), and Tower Test (measures inhibition and spatial planning). The CANTAB has tests such as Intra/Extradimensional shift (measures shifting), Spatial Working Memory and Stockings of Cambridge (measures spatial planning; Huppert et al., 1995). The Wisconsin Card Sorting Task (WCST; Berg, 1948) is the most commonly used task by neuropsychologists that assesses shifting, inhibition, rule detection, set maintenance, and concept formation (Rabin et al., 2016). Clinical behaviour scales are also used to assess EF, including the Behavior Rating Inventory of Executive Function (BRIEF; Gioia et al., 2000) and the Frontal Systems Behavior Scale (FrSBe; Grace & Malloy, 2002). Other self-report measures include questionnaires such as the Executive Function Index (EFI; Spinella, 2005) and the Learning, Executive, and Attention Functioning (LEAF) scale (for children; Kronenberger & Pisoni, 2009) as well as more specific measures such as the Ballet Executive Scale (BES; Wong et al., 2012). Self-report measures are easy to deploy and simple for participants to complete. However, when people self-report executive deficits, they often do not correlate with scores of EF tests in neuropsychological assessments (Buchanan, 2016). They may also be influenced by external factors such as anxiety or depression. Thus, it is crucial to be aware that self-report measures should not be considered proxies for neuropsychological assessments of EF.

In research settings, EF is often assessed with computerized tasks and neuroimaging. Functional methods like functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) are used to show areas of physiological and metabolic activation during EF tasks (Nowrangi et al., 2014). Also, structural methods like MRI and diffusion tensor imaging (DTI) are used for EF deficits to show areas of volume change or loss of white matter integrity (Nowrangi et al., 2014). Computerized tasks often aim to assess one component of EF, such as shifting or updating. However, even though they are designed to assess one specific aspect of EF, other cognitive processes or even factors of EF will inevitably be needed in the task, an issue known as the 'task impurity' problem (Miyake et al., 2000). The Stroop Task is a classic example of an EF task used to assess a person's attentional control and ability to inhibit responses.

Moreover, Miyake and colleagues' (2000) well-known three-latent-factor model of EF utilized nine commonly used EF tasks, with three tasks for each factor. For inhibition, the anti-saccade, stop-signal and Stroop tasks were used. For updating, the keep-track, tone monitoring, and letter-memory tasks were used. For shifting, the plus-minus, number-letter and local-global tasks were used (Miyake et al., 2000). Considering the complexity of EF and its varied definition, several different computerized tasks can be used to measure and assess EF. However, there has been a push for more ecologically valid measures of EF that include real-life functional tasks like a cooking or shopping task (Tanguay et al., 2014; McGuire, 2014).

Individual Differences in EF

Some researchers believed that individual differences in EF are entirely genetic in origin (Friedman et al., 2008). However, many researchers have found that EF is malleable, and many factors affect a person's executive functioning. Miyake and colleagues (2012) explain that while there is a significant genetic component to EF, it does not mean that an individual's EF is not amenable to training. Executive functioning varies from person to person due to many factors, including age, education, and lifestyle. Further, there has been some exciting research investigating the association between personality and executive function.

One of the most well-known and widely accepted models of personality is the Five-Factor Model. It consists of openness (e.g., open to new experiences, creative, complex), conscientiousness (e.g., caring, dependable, self-disciplined), extraversion (e.g., enthusiastic, outgoing, and social), agreeableness (e.g., sympathetic, forgiving and warm), and neuroticism (e.g., anxious, easily upset and irritable; McCrae & Costa, 1987; McCrae & Costa, 2008). Research focusing on elucidating the relationship between EF and personality has produced some consistent findings. Neuroticism is frequently negatively associated with EF; however, researchers are unsure if this is due to overlapping other traits that negatively affect cognitive performance, such as anxiety (Muris et al., 2009). Although seemingly related to self-control and goal-oriented behaviour, conscientiousness is often not significantly correlated with EF (Unsworth et al., 2009). Meanwhile, agreeableness and extraversion often have mixed findings regarding their relationship with EF. Openness is often positively correlated with EF (Murdock et al., 2013). Thus, individual personality differences may help to explain differences in EF performance.

More recently, researchers have investigated the role of athletic expertise on the relationship between EF and personality in athletes ranging from novice to super-elite. Structural equation modelling revealed that EF was significantly positively related to openness and conscientiousness, significantly negatively related to neuroticism, bi-directionally related to extroversion and unrelated to agreeableness (Vaughan & Edwards, 2020). Athletic expertise was found to moderate the relationships between personality and EF (Vaughan & Edwards, 2020). The authors suggest that these findings provide a better understanding of how athletes' individual differences may interact and influence their performance and state that future research should include several measures of EF to assess consistency across multiple related tasks (Vaughan & Edwards, 2020). In addition to teasing apart individual differences to explain variation in EF performance, it is essential for future research to use multi-modal approaches to assess EF.

Qualitative Research on EF

Unfortunately, there is a lack of research on EF utilizing qualitative methods. Previous qualitative research has explored the interplay between motivation and self-regulation in elite female athletes and generated themes related to executive processes such as planning and self-control (Jordalen et al., 2020). Qualitative researchers have also utilized qualitative methods to understand those with EF deficits (Kudlicka et al., 2017). Through semi-structured interviews, they explored both the experiences of those with Parkinson's disease and carers to see if they identified EF difficulties. While the participants had objectively mild executive deficits, they described a range of cognitive dysfunction, including executive deficits (Kudlicka et al., 2017). Another study interviewed elite trampoline athletes to break down the meaningful action and units of performance (Huaw & Durand, 2004). Huaw and Durand (2004) determined that when exercises were labelled ‘average’, the athletes felt in control of their actions, and this was deemed ‘regulating the situation’. When the athletes performed an exercise labelled ‘very good’, it was deemed ‘attentive monitoring’ and the athletes described feeling advanced and were closely monitoring their actions. However, to our knowledge, no study has ever directly explored describing and defining EF in sport through qualitative methods.

EF in Physical Activity, Exercise and Sport

Physical activity is defined as "bodily movements produced by skeletal muscles that result in energy expenditure above basal metabolic rate" (Bouchard et al., 1994). At the same time, exercise is considered "a subtype of PA that is planned, structured, repetitive, and purposive" (Berryman et al., 2017, p. 188). Finally, sports are defined as physical, organized games comprised of competition (i.e., a winner and loser) and skill (i.e., not chance; Guttmann, 1978; Suits, 2007). Sports can be differentiated into externally paced (EP) sports and self-paced (SP) sports. Externally paced (EP) or open skill sports such as tennis or team ball games are sports in which the environment controls the rate of performance, while self-paced (SP) or closed skill sports such as swimming or track and field are sports in which the athlete controls the rate of performance (Singer, 2000). Physical activity, exercise and sport are known to have many positive benefits, including preventing chronic diseases such as obesity, hypertension, cancer, depression (Warburton et al., 2006). However, more recent attention has been focused on the benefits of sport and exercise on cognitive functioning.

Among the first to evaluate the beneficial effects of exercise on EF were Hall and colleagues (2001), who conducted a literature review and found that aerobic exercise primarily improved EF. Further, Barenberg et al.’s (2011) review determined three physiological explanations to the positive relationship between exercise and EF: 1) increased oxygenation to brain areas involved in cognitive function such as the prefrontal cortex (PFC), 2) increased plasticity leading to more efficient neuronal processes, and 3) upregulation of brain neurotransmitters (i.e., norepinephrine and dopamine). Best’s (2010) review in children determined that cognitively engaging exercise produces more benefit due to the cognitive processes needed to engage in the exercise in addition to the cognitive processes needed to perform the exercise and the physiological benefits from exercise. However, there is continued debate regarding the direction of this positive relationship, with some arguing that high executive functioning leads to increased exercise and sports performance. For example, physical activity and exercise researchers found a significant relationship between planning (e.g., implementation intentions or if-then plans) and engaging in physical activity, with this relationship being moderated by EF (Hall et al., 2014). Further, Carraro and Gaudreau (2013) conducted a meta-analysis examining the effects of action and coping planning on physical activity and determined that both planning types have a medium-to-large effect on the engagement in physical activity. Lastly, Rhodes and colleagues (2020) discuss how different types of planning (i.e., action planning, coping planning, implementation intention and preparatory planning) are often used successfully as interventions to cause behaviour change, specifically within the realm of increasing physical activity. Due to evidence supporting both directions of this relationship, most researchers now believe the relationship between EF and physical activity is a dual, reciprocal relationship (Daly et al., 2015).

Many studies have been dedicated to investigating the role of exercise in executive functioning. For example, Padilla and colleagues [Padilla et al. (2013); Padilla, Pérez & Andrés (2014)] found that regular exercise in young adults is associated with better inhibition and working memory capacity. In middle-aged women, it was found that both aerobic and strength-based exercise has beneficial impacts on EF (Alves et al., 2012). Another study found that acute 30-minute bouts of either moderate or high-intensity resistance exercise significantly improved performance on two EF tasks, the

Flanker and the Go/No-Go tasks (Tsai et al., 2014). A meta-analysis of 21 studies on exercise and EF in children (6 – 12 years old), adolescents (13 – 17 years old) and young adults (18 up to age 35) determined that acute exercise was moderately, positively associated with EF, with no significant differences between the three age groups (Verburgh et al., 2014b). Furthermore, the domain the authors termed 'inhibition/interference control' seemed to be most sensitive to acute exercise (d = .56), while working memory showed non-significant effects of acute exercise. However, exercise intensity was not reported consistently throughout the 21 studies and may be a potential confounding variable (Verburgh et al., 2014b). Lastly, a more recent meta-analysis (Zhu et al., 2020) evaluated the effect of open-skilled (or EP) versus closed-skill (or SP) exercise on cognition across the lifespan. Among the 15 cross-sectional studies included in the meta-analysis, it was determined that open-skill exercise compared to closed-skill exercise was superior for EF with an overall effect size of .3 (Zhu et al., 2020). While it is apparent that many forms of exercise have a beneficial impact on EF across the lifespan through multiple methods, less is known about the specifics of these improvements. Is it sport-specific? Do certain EF processes have more gains than others? There are lots of questions that remain unanswered.

EF Differences based on Sport Type

There has been a more recent effort to investigate differences in EF based on the type of sport. Jacobson and Matthaeus (2014) investigated the relationship between EF and sport type as well as sport level (delineated as high-skilled or recreational) in young adults (M = 20.13 years) utilizing tasks assessing decision making, problem-solving and inhibition. This study found that SP athletes scored the highest on an inhibition task (D-

KEFS Color-Word Interference Test), followed by EP athletes and nonathletes. EP athletes scored highest on the problem-solving task (D-KEFS Tower test), followed by SP athletes and nonathletes. Intriguingly, there were no significant differences between EP athletes, SP athletes and nonathletes in processing speed, vocabulary or decision making; however, the authors explain that decision making was measured using the Tower time-per-move ratio, which could be misleading if a participant is attempting multiple moves with no forethought (Jacobson & Matthaeus, 2014). This study was one of the first to investigate EP and SP differences in EF but failed to provide a comprehensive assessment of EF.

Similarly, Ballester et al. (2019) studied the effect of chronic sport participation (EP versus SP) on vigilance and inhibitory control in young adults. However, the results of this study, in contrast to Jacobson and Matthaeus (2014), showed that EP athletes had significantly greater inhibitory control than both nonathletes and SP athletes (Ballester et al., 2019). Interestingly, cardiovascular fitness was not a significant moderator of the differences in inhibitory control between EP and SP athletes (Ballester et al., 2019). Thus, it appears there are contradictory findings concerning inhibition in SP and EP athletes.

There has also been research on sports differences that use different categorizations of sports. For example, Holfelder and colleagues (2020) investigated the role of sport type (grouped as open-skill or closed skill) and level (elite versus amateur) on hot EF (e.g., motivationally driven, affective conditions) and cool EF (e.g., non-affective conditions) in adolescents between the ages of 13 and 15. For hot EF, participants performed one task: The Game of Dice task. For cold EF, they performed four standard tests of EF: Trail-Making Test (TMT), Trail-Walking-Test (TWT), Flanker task, and n-back-task. There were no significant differences between sport types, except for the TWT in which open-skill athletes performed significantly better than closed-skill athletes. There were no significant differences between sport levels, except for the TWT in which elite athletes outperformed amateur athletes. Additionally, Chueh and colleagues (2017) found that athletes have superior visuospatial attention and memory performance than nonathletes. They found no differences between open and closed-skill athletes. Another recent study (Krenn et al., 2018) also aimed to compare differences in EF by sport type but divided the sports into static (i.e., swimming, weightlifting), interceptive (i.e., tennis, combat sports) and strategic (i.e., ice hockey, volleyball) sports. Krenn and colleagues (2018) were one of the first to measure EF using Miyake et al.'s (2000) framework with tasks assessing inhibition (Flanker task), shifting (Flanker task-switching), and updating (2-back). They only found significant differences for mean reaction times and shifting, with strategic sport participants having better performance than the static or interceptive participants. While Krenn and colleagues (2018) did assess the three latent factors, they only had one task for each factor. Further, Yu and Liu (2020) investigated differences in EF in athletes from interceptive or strategic sports using a revised attention network task. They also assessed the related blood oxygen changes in the right frontoparietal network using fNIRS. As expected, they found that athletes performed significantly faster and more accurately than nonathletes. Interestingly, strategic athletes performed with greater accuracy but had longer reaction times than interceptive athletes. The greater accuracy and longer reaction time were related to significant activation of the right dorsolateral prefrontal cortex (rdLPFC) and the right inferior frontal gyrus (rIFG; Yu & Liu, 2020). More recently, Koch and Krenn (2021) investigated EF differences between elite athletes in open-skill versus closed-skill sports with a focus on the role of their total involvement in both types of sports until eighteen years old. They found that open-skill athletes had greater performance on working memory and cognitive flexibility tasks. They also found that elite closed-skill athletes who also had high involvement in open-skill sports until 18 had greater performance on the working memory and cognitive flexibility tasks.

Overall, while some recent research investigated differences in EF by sport type, the findings and categorizations of sport are varied and there is a lack of research assessing the three latent factors with more than one task.

EF Performance in Specific Sports: Soccer and Volleyball

There has also been an interest in investigating EF performance in elite athletes of specific sports, including soccer. In the last ten years, a proliferation of research has aimed to assess EF in young soccer players in an attempt to predict both what makes a top-tier athlete and who will develop into a top-tier athlete. For example, Verburgh and colleagues (2014a) determined that highly talented youth soccer players had significantly better motor inhibition and sustained attention than amateur players. Meanwhile, Vestberg and researchers (2012) also attempted to determine if EF performance could predict the success of soccer players from both a high division and low division as well as a norm group. First, as expected, the researchers found that both division players outperformed the norm group in tests of EF, and the high division group outperformed the low division group (Vestberg et al., 2012). Second, they found a significant association between EF performance and the number of goals and assists players scored two seasons later. The same group of researchers later endeavoured to see if EF could predict sports performance in a group of adolescent elite soccer players (Vestberg et al., 2017). They found that not only did the elite soccer players perform better than the norm, but their EF task performance also correlated with the number of goals players scored throughout a season, even when controlling for age, length of play, and intelligence (Vestberg et al., 2017). Thus, it seems that not only do elite soccer players have better EF performance, but EF may also be predictive of future sport success.

However, research has not focused solely on soccer players, with the EF of volleyball players also being an area of interest for researchers. First, in 2013, Alves and colleagues compared 87 professional volleyball players to 67 nonathlete controls and determined that the professional volleyball players had significantly better performance speed on two EF tasks and a visuospatial processing task. Then, Bisagno and Morra (2018) examined the relationship between working memory performance and the practical execution of the ‘third touch’ volleyball technique in 120 volleyball players ranging in age from 6 to 26 years old. They found that working memory capacity was the best predictor of correct execution of the third touch. Meanwhile, Montouri and colleagues (2019) investigated differences in task switching performance in 36 elite volleyball players based on position (strikers, defenders, and mixed). They found that each role had unique characteristics in performance, with strikers having the fastest reaction times but the mixed group having greater accuracy. These are some of the first findings investigating position differences in EF performance. Altogether, these findings further provide support for the athletic advantage in EF across many sports.

EF and Sports-Related Concussion

Injuries in sports are common, and head injuries are no exception. Approximately 1900 Canadians were hospitalized between 2017 and 2018 for sports-related brain injuries, a 5% increase from 2013-2014 (Canadian Institute for Health Information, 2019). Sports-related concussions (SRC) are a specific type of brain injury defined as a "traumatic brain injury induced by biomechanical forces… caused either by a direct blow to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head…[and] typically results in the rapid onset of short-lived impairment of neurological function that resolves spontaneously" (McCrory et al., 2017, p.839). SRCs often have a diverse range of signs and symptoms, including dizziness, feeling in a fog, headaches, nausea and may but does not have to involve loss of consciousness (McCrory et al., 2017). Most symptoms and cognitive deficits that an athlete experiences following an SRC resolve within 7 – 10 days, although they may be prolonged (Karr et al., 2014b).

In terms of the impairment in cognitive functioning, the effects of SRC on EF have been extensively studied. Research has shown that any injury that threatens the integrity of the brain will lead to some EF impairment, and worse EF impairment and longer recovery time are associated with earlier concussions (Garcia-Barrera, Agate, Wong, Smart & Karr, 2019). Further, studies have determined that EF deficits can appear almost immediately after an SRC and may linger for at least a month (Mayr et al., 2014; Howell et al., 2013; Tapper et al., 2017; Lax et al., 2015). For example, Mayr and colleagues (2014) tested 16 individuals with an SRC 48 hours after the injury, and then seven days, 14 days, and 28 days later as well as 16 matched (in age, sex, weight, sport, health) controls at the same time intervals. They utilized a switching task and found that the switch-cost (the time it takes to respond to a trial that was not a repeat of the previous) was significantly greater in the concussed athletes than the control-group athletes at each time interval tested. Further, in a large 3-year cross-sectional and longitudinal multiple cohort study of 211 adolescent hockey players, 25 experienced a concussion and were assessed each day following the injury for seven days. They found that concussion history and severity were negatively associated with cognitive flexibility (Lax et al., 2015). Interestingly, the female athletes had significantly greater initial deficits on the Stroop task (assesses inhibition and cognitive flexibility) than male athletes. However, after these early deficits, the female athletes improved quicker than the males at 1-month post-concussion (Lax et al., 2015). Lastly, it is important to note that these deficits may last longer than a month, especially if there have been multiple previous SRCs. Seichepine et al. (2013) examined EF (measured by the BRIEF) in current and retired college and professional football players (all with a history of at least one concussion). In comparison to the published normative data, the football players reported more prevalent issues with EF. In addition to elevated overall scores on the BRIEF, they also found elevated scores on specific indices related to behavioural and emotional control and problem-solving through planning, organization, and sustaining effort (Seichepine et al., 2013). So, there is still a need to investigate SRC effects in different sport types with a wide-ranging EF assessment to better understand the mechanisms and factors behind long-term sequelae of executive dysfunction following an SRC.

Qualitative Research on SRC

In the past few years, research investigating SRC has shifted to include more qualitative approaches. Iadevaia and researchers (2015) interviewed seven adolescents and their parents (separately) to determine their quality of life one year after an SRC. The authors identified four themes: (1) significant effect of symptoms, (2) feelings of frustration, (3) influence on school attendance and activities, and (4) nature of interpersonal and team relationships. They conclude that the adolescents' experiences of an SRC affected them in many domains of life, including emotional, social and academic (Iadevaia et al., 2015). However, they did not investigate cognitive symptoms such as EF in detail. McLeod and colleagues (2017) also interviewed adolescent athletes but between 15- and 30-days post-concussion and found similar themes emerge as Iadevaia et al. (2015), including symptom effects, emotional impact, effect on schooling, and effect on socializing.

Another study explored 20 NCAA varsity football players' SRC recovery and return to play experiences using qualitative semi-structured interviews (Tjong et al., 2017). Tjong and colleagues (2017) identified themes such as issues of underreporting and the culture of the NCAA football league and increasing concussion awareness and education but did not report on cognitive functioning throughout the recovery process. There is also a wealth of qualitative research investigating concussion knowledge across various populations, including athletes, coaches and health professionals (Mann et al., 2017; Yeo et al., 2015; Williams et al., 2016). More recently, Davies and researchers (2020) interviewed eight adolescents and young adults (and six parents) to explore social and emotional support following persistent concussion symptoms. They found that many participants experienced emotional distress, including depression/sadness, anxiety/stress, irritability, and isolation but similar to previous studies, they did not investigate potential cognitive difficulties (Davies et al., 2020).

There has also been qualitative research investigating concussion symptoms in nonathletes. For example, Ierssel and colleagues (2020) conducted ten focus groups with those experiencing persistent concussion symptoms and semi-structured interviews with clinicians. Thematic analysis identified three main themes that help to explain how post-concussion symptoms affected the participants' lives: 1) functioning, 2) barriers and facilitators, and 3) capacity. Within the functioning theme, participants discuss difficulties with learning and applying knowledge. Further, one participant describes difficulty with decision-making but not in the context of executive functioning (Ierssel et al., 2020). Lastly, a recent study investigated the differences in symptom reporting of mild traumatic brain injury between structured interviews and questionnaires (Emmert et al., 2021). The researchers determined that symptom reporting varied depending on if it was an open- or closed-ended question, with participants reporting more symptoms with closed-ended questions (Emmert et al., 2021). Closed-ended questions were also more closely associated with the symptoms reported in the questionnaires (Emmert et al., 2021). However, the researchers note that this may be partly because of how the questions themselves were asked, with the open-ended questions having participants discuss their acute symptoms. In contrast, the closed-ended question asked them to report all symptoms in the last three months (Emmert et al., 2021).

So, while there has been a rise in current research utilizing qualitative methods to explore the athlete's experiences of SRC, researchers are primarily focusing on quantitative methods for symptomology and cognitive recovery, and none have used a qualitative design to understand EF deficits.

Conclusions

EF is a psychological construct that helps explain the organization, planning and execution of goal-oriented behaviour. It develops throughout childhood and adolescence, peaking around the mid-twenties before declining in older age. The neural correlates of EF provide us with a better understanding of the construct with three primary circuits that begin in the frontal lobes and project throughout the whole brain. Further, there are many modes of measuring components of EF, including questionnaires and computerized tasks. Research has shown that not only is it malleable to development and certain lifestyle factors such as sport and exercise, but athletes also regularly show higher EF than nonathletes. There has been a surge of research investigating differences in EF based on sport and specific sport EF advantages. However, playing sports also comes with an increased risk of concussion, which can negatively affect a person's executive functioning. To conclude, the field of EF research is vast and diverse, similar to the construct it studies, with many operationalizations and measurement approaches that ultimately provide a comprehensive albeit complicated interpretation of EF.

Chapter 2: A Quantitative Investigation of Executive Function: The Role of Physical Activity, Sport, and Concussion History

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Abstract

Introduction: Many factors, including physical activity, sports participation, and concussion, can affect executive functioning. Physical activity and sport have been found to have a beneficial effect on executive function, while concussion history may have a detrimental effect. Previous research has yet to investigate the combined effects of physical activity, sports participation and concussion history utilizing a comprehensive, remote assessment of executive function. This study aims to examine the effects of physical activity, previous sports participation and concussion history on subjective (e.g., questionnaire) and objective measures (e.g., latent variables) of executive functioning in young adults.

Methods: 247 Canadian university students (ages 18 – 25; 83% female) completed a remote assessment of executive function (nine computerized tasks and a behavioural self-report) in addition to questionnaires and items assessing weekly physical activity, athletic status, and concussion history. Structural equation modelling and linear regression were used to predict performance on executive function measures. The structural equation model was a three-factor model of executive function with shifting, updating and inhibition.

Results: The three-factor measurement model of executive function fit the data adequately: , $\chi^2 = 26.10$, *df* = 17 *p* = 0.07, CFI = 0.97, TLI = 0.95, RMSEA = 0.05 [90% CI: 0.00–0.09], SRMR = 0.04. Then, the three-factor structural equation model of executive function also fit the data adequately: $\chi^2 = 66.38$, *df* = 51, *p* = 0.07, CFI = 0.95, TLI = 0.93, RMSEA = 0.04 [90% CI: 0.00–0.06], SRMR = 0.05. Using structural equation modelling, no direct relationship was found between the factors of executive function and the predictor variables (i.e., age, physical activity, concussion history, and athletic status). Sex was significantly related to inhibition, $b = 0.52$, $p = 0.02$, such that males had greater inhibition. For the regression, physical activity ($b = 0.09$, $p < .01$), concussion history ($b = 3.29$, $p < .05$) and athletic status ($b = -4.01$, $p < .05$) were found to be significant predictors for the behavioural self-report measure of executive function (i.e., Executive Function Index).

Conclusions: Concussion history, physical activity, and athletic status were all predictive of subjective executive function but not objective measures of executive function. Mixed findings in the extant literature regarding sex differences and executive function require continued research to understand better the relationship and mechanisms behind the potential differences. These findings offer support for the differentiation between subjective and objective measures of executive function when investigating their relationship with physical activity, sport participation, concussion history, age and sex.

Keywords: executive function, neuropsychology, physical activity, concussion, sport

Introduction

Despite how often executive function (EF) is studied, the concept remains ill-defined with many theoretical frameworks and definitions [e.g., Miyake et al.'s (2000) three latent factor approach; Lezak et al.'s (2004) definition; Jurado & Roselli's (2007) definition; etc.]. Broadly, it is a high-level cognitive function employed during novel situations by integrating lower-level processes to create and regulate goal-directed behaviours (Duggan & Garcia-Barrera, 2015). In the past, there has been considerable debate on whether EF is a unitary, singular construct or if it consists of diverse, separable functions. Interdisciplinary research, including experimental psychology, neuropsychology, and neuroscience, has determined that separate unique EFs can be isolated. However, all EFs are interconnected within distributed networks throughout the brain but mainly involve dorsolateral prefrontal, anterior cingulate, and parietal cortices (Niendam et al., 2012).

Due to the elusive and complex nature of EF, its measurement can be quite varied. One of the most prolific approaches to studying and measuring EF was first discussed in Miyake and colleagues' (2000) seminal paper. They determined three latent factors of EF, shifting, updating, and inhibition, that were distinguishable but moderately correlated. Shifting is thought to be the ability to change or shift perspective, attention, or responses (Diamond, 2006; Miyake et al., 2000). Updating (e.g., the updating of working memory) is the ability to hold, monitor and code information through the manipulation or revision of pertinent information within one's working memory (Diamond, 2006; Miyake et al., 2000). Lastly, inhibition is the ability to suppress inappropriate responses, stay focused, and ignore distractions (Miyake et al., 2000). These three latent factors are lower-order

EF processes that work together to produce higher-order EF, such as decision-making, problem-solving, and planning (Gilbert & Burgess, 2008; see Figure 2).

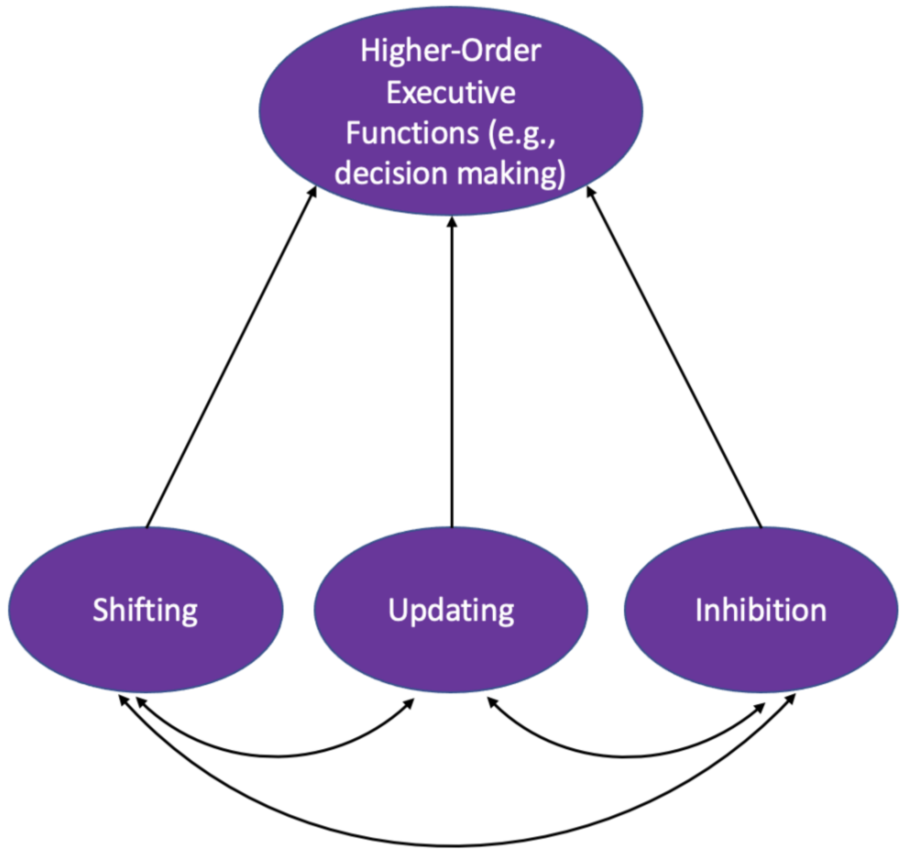

Figure 2. Schematic of lower and higher-order EF.

This approach to measuring and conceptualizing lower-order EF processes is attractive due to its ease of assessment in laboratory environments with computerized tasks. However, other approaches to assessing EF include self-report measures such as the Executive Function Index (EFI; Spinella, 2005). The EFI was designed to assess subjective executive functioning in normal individuals, which is unique, considering most other self-report EF measures were developed using clinical populations (Spinella, 2005).

It has five subscales that assess real-life behavioural executive functioning: motivational drive, organization, impulse control, empathy, and strategic planning (Spinella, 2005).

The use of self-report methods or computerized tasks assessing shifting, updating and inhibition both have their relative advantages and disadvantages. The advantages of self-report methods include being more ecologically valid, easy to deploy, and simple for participants to complete. However, when people self-report EF, they often do not correlate with scores of EF tests in neuropsychological assessments (Buchanan, 2016) and may be influenced by external factors such as anxiety or depression. Meanwhile, the strengths of computerized tasks include being objective measures of performance with standardized administrations and stimulus presentation. However, even though most EF tasks are designed to assess one specific EF process such as inhibition, other cognitive processes or even factors of EF will inevitably be needed in the task, an issue known as the 'task impurity' problem (Miyake et al., 2000). Therefore, it may be beneficial to use multiple methods to measure EF when assessing potential relationships with other variables, such as physical activity and sport.

The Malleability of EF – Physical Activity

Physical activity is well known to have many positive benefits, including preventing chronic diseases such as obesity, hypertension, cancer, depression (Warburton, Crystal Nicol, & Bredin, 2006). However, more recent attention has been focused on the benefits of exercise on executive functioning (Barenberg et al., 2011). Among the first to review the beneficial effects of exercise on EF were Hall and colleagues (2001), who found that aerobic exercise primarily improved EF in older adults. In children, Best's (2010) review determined that while all exercise is beneficial, cognitively engaging exercise produced the most benefit to EF.

Since then, many studies have been dedicated to investigating the role of exercise in executive functioning. For example, Padilla and colleagues [Padilla et al. (2013); Padilla et al., (2014)] found that regular exercise in young adults is associated with better inhibition and working memory capacity. Another study found that acute 30-minute bouts of either moderate or high-intensity resistance exercise significantly improved performance on two EF tasks, the Flanker and the Go/No-Go tasks (Tsai et al., 2014). A meta-analysis of 21 studies on exercise and EF in children (6 – 12 years old), adolescents (13 – 17 years old) and young adults (18 up to age 35) determined that acute exercise was moderately, positively associated with EF, with no significant differences between the three age groups (Verburgh et al., 2014b). Furthermore, the component these authors named "inhibition/interference control" seemed to be most sensitive to acute exercise (d = .56).

With these findings, there is continued debate regarding the direction of this positive relationship, with some arguing that high executive functioning leads to increased exercise. Most researchers now believe it is a dual, reciprocal relationship (Daly et al., 2015) and there are a few proposed mechanisms including 1) improved vascularization and angiogenesis (formation of new blood vessels) in the brain, 2) upregulation of brain-derived neurotrophic factor (BDNF) and 3) cognitively demanding physical activity engaging EFs and other cognitive processes leading to increased activation within the prefrontal cortex and neurogenesis in the hippocampus (Churchill et al., 2002; Szuhany et al., 2015; Best, 2010; Tomporowski & Pesce, 2019). While it is apparent that many forms of exercise have a beneficial impact on EF across the lifespan through multiple proposed mechanisms, less is known about the specifics of these improvements. Do certain EF processes have more gains than others? Does physical activity differentially impact subjective behavioural EF measures in comparison to objective computerized EF tasks? There are lots of questions that remain unanswered.

The Malleability of EF – Sports

Not only does physical activity seem to be beneficial for executive functioning, but sports, specifically, may lead to a unique ‘athletic advantage’. Athletes frequently perform better on a range of EF tasks, including inhibition, updating, switching, decision making and problem-solving tasks (Alves et al., 2013; Jacobson & Matthaeus, 2014; Chueh et al., 2017; Vestberg et al., 2017; Ballester et al., 2019; Yu & Liu, 2020). Further, elite athletes tend to outperform amateur or novice athletes on EF tasks (Vestberg et al., 2012; Verburgh et al., 2014a; Kida et al., 2005). However, there is continued debate if higher levels of expertise and skill in sport lead to increased executive functioning or if superior executive functioning leads to better sport performance.

Diamond and Ling (2016) propose that the skills acquired (e.g., while playing a sport) and the cognitive demands that are utilized have more of a benefit to EF than the physiological explanations. This aligns with previous research that has found that cardiovascular fitness is not a significant moderator in athletes’ EF performance (Ballester et al., 2019). Relatedly, Moreau and Conway (2014) advise that the greatest cognitive gains are acquired when the training contains complexity, novelty, and diversity which are all frequent within a sporting game. Further, Yu and Liu (2020) investigated differences in EF in athletes from differing sports. They found that the athletes who had greater accuracy also had significant activation of the right dorsolateral prefrontal cortex and the right inferior frontal gyrus. Thus, it appears there may be aspects unique to sport, outside of physical activity, such as the cognitive demands related to complex motor movements, strategy and gameplay, that are beneficial to executive functioning. However, with increased physical activity and sport participation, one is at increased risk of obtaining a concussion, which can have detrimental effects on executive functioning.

The Malleability of EF – Concussions

Concussions have a diverse range of signs and symptoms, including dizziness, feeling in a fog, headaches, nausea and does not have to involve loss of consciousness (McCrory et al., 2017). Most symptoms and cognitive deficits that a person experiences following a concussion resolve within 90 days, although different cognitive functions have varying recovery rates (Karr et al., 2014b; Kunker et al., 2020). Regarding the impairment in cognitive functioning, the effects of concussions on EF have been extensively studied (Karr et al., 2014b). Research has shown that any injury that threatens the integrity of the brain will lead to some EF impairment, and worse EF impairment and longer recovery time are associated with earlier concussions (Garcia-Barrera et al., 2019). Further, studies have determined that EF deficits can appear almost immediately after a concussion and may linger for at least a month (Mayr et al., 2014; Howell et al., 2013; Tapper et al., 2017; Lax et al., 2015). For example, Mayr and colleagues (2014) tested 16 individuals with an SRC 48 hours after the injury, and then seven days, 14 days, and 28 days later as well as 16 matched (in age, sex, weight, sport, health) controls at the same time intervals. They utilized a switching task and found that the switch-cost (the time it takes to respond to a trial that was not a repeat of the previous) was significantly greater in the concussed athletes than the control-group athletes at each time interval tested. Similarly, a meta-analysis of the effects of military blast-related concussions found EF to be the most sensitive, with shifting being particularly affected (Karr et al., 2014a). Therefore, previous research suggests that concussions have a detrimental effect on cognitive functioning, particularly executive functioning.

Lastly, it is essential to note that these deficits may last longer than a month, especially if there have been multiple previous concussions. Seichepine et al. (2013) examined EF (measured by the BRIEF) in current and retired college and professional football players (all with a history of at least one concussion). In comparison to the published normative data, the football players reported more prevalent issues with EF. In addition to elevated overall scores on the BRIEF, they also found elevated scores on specific indices related to behavioural and emotional control and problem-solving through planning, organization, and sustaining effort (Seichepine et al., 2013). Further, researchers found that while military personnel experienced subjective executive dysfunction following a traumatic brain injury (66% classified as mild), they had no objective dysfunction measured through computerized tasks (Schiehser et al., 2011). So, there is still a need to investigate the concussion effects with a wide-ranging EF assessment to understand better the mechanisms or variables behind long-term sequelae of both subjective and objective executive dysfunction following a concussion.

Current Study

While past research has focused on investigating the effects of physical activity, sport, and concussion history on EF, none have looked at the combined effects using a robust assessment of EF with two analyses: 1) a latent variable approach using nine computerized tasks and 2) a regression model to predict a subjective, self-report measure of EF. Considering researchers have yet to investigate the potential differential effects of physical activity, sport participation and concussion history on subjective and objective measures of EF, this study will elucidate the effects on EF in both reported everyday behaviour and in computerized environments which can provide insight into our conceptualization and measurement of EF and thus, stimulate future research. Thus, this study will investigate these differences in EF based on physical activity, athletic status, and concussion history. Further, we will investigate these variables to predict not only the three latent factors of EF but also a self-report measure of EF. Consistent with previous studies, we hypothesize that greater physical activity levels will predict better performance on all measures of EF. We also predict that athletic status will be positively related to all measures of EF. Thirdly, we predict that concussion history will negatively predict all measures of EF. However, considering that subjective, self-report measures of EF tend to be more ecologically valid and have more real-world implications, we believe that the relationship between physical activity, athletic status and concussion history will be more pronounced for the self-report measure than the performance measures.

Methods

Participants

Participants consisted of 247 Canadian university students aged 18 to 25 (*M* = 20.10, *SD* = 1.86; 83% female). Inclusion criteria included age (18 to 25 years old), normal or corrected-to-normal vision, no history of neurological (excluding concussion) or cardiovascular disease, and no medication or drugs that may affect cognition at the time of testing. Participants were recruited from the local university's psychology research participant pool and were awarded one-course credit for participating.

Procedure

Participants completed a remote online study that lasted approximately one hour. There were nine computerized tasks along with demographic questions and two questionnaires. Gorilla (www.gorilla.sc) was used to collect data for the study. Gorilla is a cloud software platform specifically developed for the behavioural sciences (Anwyl-Irvin et al., 2019). Participants were able to complete this study via a desktop computer or laptop. Ethics approval for this study was obtained from the University of Victoria's Human Research Ethics Board (protocol # #20-0535).

Computerized Tasks

Updating

N-back. The 2-Back task measures updating of working memory (Kirchner, 1958). A series of letters will appear on the screen. Each letter appears on the screen for 400ms. For each letter, participants must click "F" for " yes" if the current letter is the same as two letters ago, or "J" for "no" if it is different from 2 letters ago. There were 30 targets (e.g., the letter was the same as two letters before) for a total of 180 trials. The endogenous variable was the proportion of correct responses.

Reading Span. This task was the second measure of updating working memory based on the original task by Daneman and Carpenter (1980) with computerized modifications (from Unsworth et al., 2009). Initially, participants were shown a string of letters and are told to remember them. Then, participants had to read a series of short sentences and answer if they were true or false (e.g., 'Oranges live in water', 'Chickens lay eggs’). Finally, the participants had to type the original string of letters into a text box on the screen. Participants initially completed practice trials of recalling the letter strings and answering the true or false statements before beginning the trials. The letter strings ranged from 2 letters to 7 letters, and the endogenous variable is the proportion of correct text entry responses.

Digit Span Backwards (DSB). DSB also measures updating and is adapted from the Weschler Adult Intelligence Scale (WAIS; Weschler, 1955). Participants are shown a string of numbers and then must repeat them backward by clicking on an answer pad on the screen. Following two practice trials, five lists of two digits are presented. They must succeed on a minimum of four trials to move on to the next level where three digits are presented. This procedure continues until participants fail on four trials at a given level. Participants receive a final score based on the proportion of correct number entries.

Inhibition

Simon Task. The Simon task is a measure of inhibition (Simon, 1969). There is a fixation cross in the middle of the screen, and the words "Left" or "Right" will appear randomly on either side of the fixation cross. If the word “Left” appears on either side, participants must click “F”. If the word “Right” appears on either side, participants must click “J”. There were 100 trials with an equal number of each stimulus presented. The endogenous variable is the proportion of correct responses.

Stop-Signal Delay. Stop-Signal Delay also measures response inhibition (Logan, Cowan, & Davis, 1984). Left and right-pointing arrows are presented inside a white circle. Participants must click "F" if the arrow points left and "J" if the arrow points right. In some trials, the circle will flash red (the stop-signal), indicating that the participant should not respond. After eight practise trials with feedback, participants completed 92 trials. The endogenous variable is the proportion of correct responses.

Flanker. The Flanker task is another inhibition task as it measures participants' ability to inhibit irrelevant information (Eriksen & Eriksen, 1974). A row of five arrows is presented; all the arrows face the same direction except the middle arrow. It may face the same direction as the four other arrows (congruent) or face the opposite direction of the other four arrows (incongruent). If the middle arrow is facing left, participants must click "F", but if the middle arrow is facing right, the correct response is "J". After 12 practice trials (six congruent and six incongruent), there were four blocks of 24 trials (96 total). The endogenous variable is the difference in reaction time between congruent and incongruent trials.

Shifting

Modified Wisconsin Card Sorting Task (WCST). The WCST measures a participant's ability to switch between three sets of rules in a single task (Kongs et al., 2000). Participants are presented with a target card and asked to categorize it with one of four reference cards. If the participants categorize the target card with a reference card correctly, they will be shown a thumbs-up before starting the subsequent trial. If they are incorrect, they will be shown a thumbs down. In the original WCST, the rule changes after participants have gotten ten consecutive trials correct. However, in this modified version, the categorizing attribute randomly changes after ten trials and the participants must adjust accordingly. Another modification is that participants are told the cards can be categorized by one of three attributes: colour (red, green, blue, yellow), shape (circle, cross, star or square) and number (1, 2, 3, or 4). There are 64 trials. The endogenous variable is the proportion of correct responses.

Alternate Task Switching (ATS): ATS measures a participant's ability to switch between two sets of rules in a single task (Rogers & Monsell, 1995). The stimulus can be a square or rectangle that is blue or green (i.e., blue rectangle, green rectangle, blue square, green square) and is presented at the top or bottom of the screen. Response keys are "F" and "J". If the stimulus is presented at the top of the screen, the participant must click "F" if it is blue and "J" if it is green. If presented at the bottom of the screen, participants must click "F" if it is a square and "J" if it is a rectangle. There are 100 trials following 25 practice trials. The endogenous variable is the proportion of correct responses for the trials.

Cued Task Switching (CTS): CTS measures a participant's ability to switch between two sets of rules in a single task (Allport, Styles, & Hsieh, 1994). There are four sets of stimuli that vary by colour and shape (square or rectangle; blue or green). First, a word is presented (either colour or shape), followed by one of the four stimuli. If the word is "colour", participants must click "F" if the shape is blue and "J" if it is green. If the word is "shape", participants must click "F" for square and "J" for a rectangle. After 25 practice trials, there are 100 trials. The endogenous variable is the proportion of correct responses for the trials.

Questionnaires

Demographics

We asked basic demographic questions, including age, sex, concussion history, and athletic status. Concussion history was assessed with one item asking participants to select between choices of having experienced none, one, two, or three or more concussions. Athletic status was assessed with an open-ended question asking participants to enter their highest level of sport played. The responses were coded as ‘0’ = never played/not an athlete, ‘1’ = High school/community league level or lower, ‘2’ = Club level, ‘3’ = Provincial or Varsity level, ‘4’ = National or International level.

Self-reported, behavioural measure of EF

The EFI is a brief 27-item questionnaire with items assessing subjective EF through five subscales: motivational drive, impulse control, strategic planning, empathy, and organization (Spinella, 2005). Motivational Drive (e.g., activity level and drive) is assessed with items like, “*I have a lot of enthusiasm to do things”.* Impulse Control (e.g., risk-taking, substance use, excessive spending) is assessed with items like "*I lose my temper when I get upset* (reverse scored)”. The Strategic Planning subscales reflect tendencies to think ahead and plan (e.g., the anticipation of consequences, saving money) and is assessed with items like “*I think about the consequences of an action before I do it*". The Empathy subscale, which measures concern for the well-being of others, prosocial behaviours, and a cooperative attitude, is assessed with items such as "*I don’t like it if my actions or words hurt someone else*”. Lastly, the Organization subscale (i.e., the ability to carry organized goal-directed behaviour such as multitasking) is assessed with items such as “I have trouble summing up information in order to make a decision with it” (reverse-scored). All items are rated on a 5-point Likert scale from 1 ("Not at all) to 5 ("Very much"), with higher scores indicating higher levels of executive functioning.

Physical Activity

The Godin-Leisure Time Physical Activity questionnaire was used to assess leisure-time physical activity (Godin & Shephard, 1985). The questionnaire asks participants to report how many times in 7 days they engage in strenuous (e.g., running), moderate (e.g., tennis) and mild exercise (e.g., yoga) for more than 15-minute increments. The dependent variable is the weekly leisure time activity score which is calculated with the following equation:

Weekly Leisure-time Score = (9 × Strenuous) + (5 × Moderate) + (3 × Mild).

Statistical Analysis

Descriptive statistics, including means, standard deviations, kurtosis, and skewness, were calculated for the nine manifest variables. Pearson correlations were also used to test the association between these variables. An alpha level of $\leq .05$ was used as a cutoff for statistical significance. An initial statistical power analysis was performed for sample size estimation. With an alpha = .05, power = 0.80 and five predictors, the projected sample size needed for a medium effect size (GPower 3.1; Faul et al., 2007) was approximately N = 92 for a linear multiple regression. For the structural equation modelling, with an alpha = .05, and power = 0.80, the projected sample size needed was approximately 158. Thus, our sample size of N = 247 was determined to be more than adequate.

The hypothesized model was tested in two steps. First, a confirmatory factor analysis (CFA) was conducted to create a measurement model with an adequate fit to the data. Second, the structural equation model (SEM) was determined after the CFA was tested. Structural equation modelling was used to emphasize the latent factors' construct variance and minimize variance related to the specific computerized EF tasks.

First, we tested the fit of a three-factor model based on Miyake and colleagues' (2000) model with shifting, updating, and inhibition as latent factors. The model's fit was assessed using the Comparative Fit Index (CFI), the Tucker Lewis Index (TLI), the standardized root mean square residual (SRMR), and the root mean square error of approximation (RMSEA). Following guidelines for good fit, values below 0.08 for the SRMR, below 0.06 for the RMSEA, and above 0.90 for the CFI and TLI indicate a good model fit (Hu & Bentler, 1999). We then attempted to test the fit of a nested, bifactor model based on Friedman and colleagues (2008) model with shifting, updating and common EF. This model did not converge and so we decided to use the three-factor model for our analysis. Thus, the three-factor model was used to investigate the relationship between concussion history, athletic status, physical activity, age, and sex and the latent factors, inhibition, shifting and updating.

Lastly, multiple linear regressions were used to examine the behavioural measure of EF (using EFI total scores). Age, sex, concussion history, athletic status, and physical activity were included simultaneously as dependent variables. Regression coefficients were assessed in terms of statistical significance (p <.05). Descriptive statistics were also calculated for these variables. The analyses were conducted using the statistical computing environment 'R Studio' version 1.2.1335.

Exploratory Follow-up Analyses

Lastly, five multiple linear regressions were used to examine the five subscales of the EFI: Motivational Drive (MD), Impulse Control (IC), Organization (ORG), Strategic Planning (SP), and Empathy (EM). Following the same method as the previous regression, age, sex, concussion history, athletic status, and physical activity were the dependent variables.

Results

Descriptive and Preliminary Analyses

The data was initially screened for univariate and multivariate outliers and normality. First, univariate outliers were identified using the 1.5 times the interquartile range criterion. Using this method, we identified 32 univariate outliers (13% of overall sample) within the nine EF task variables and removed them from the dataset (for a total N of 215 for the SEM analysis). Then, we examined the data for multivariate outliers using Mahalanobis distance across the nine EF variables. No multivariate outliers were identified. Missing data (< 1%) was addressed using full information maximum likelihood estimation.

Descriptive statistics of the variables included in the SEM and regressions were determined to examine each variable's normality. Cued Task Switching and Alternate Task Switching accuracy variable (proportion of correct responses) were arcsine transformed to achieve normality (see Table 1). The Flanker RT difference variable was scaled from milliseconds to seconds and reversed so that higher RT indicated better performance. Pearson's correlations were calculated to examine the relationships between the nine variables, and the correlation coefficients are presented in Table 2.

Descriptive statistics were also calculated for the EFI, Godin Leisure-Time Physical Activity, concussion history, and athletic status. The EFI was normally distributed with an average score of 97.76 (*SD* = 10.72). We identified three outliers within scores for the Godin-Leisure Time Physical Activity. After their removal, it was normally distributed with a mean of 51.17 (*SD* = 26.23). Thus, for the regressions, there were a total of 244 participants. Approximately one-quarter (25.8%) of the sample had experienced at least one concussion. Regarding athletic status, 14.75% reported never playing sports/not an athlete, 30.32% reported having played at the high school/community league level or lower, 31.14% reported having played at the Club level, 15.98% reported playing at the Provincial or Varsity level, and 7.79% reported playing at the National or International level. This variable was collapsed into 'Non-athlete' (14.75%) and 'Athlete' (85.25%). Lastly, categorical variables were dummy coded for the regression analysis (e.g., sex: male = 0, female = 1; Concussion history: No concussion history = 0, Concussion history = 1; Athletic status: Non-athlete = 0, Athlete = 1).

Structural Equation Modelling (SEM)

The confirmatory factor analysis measured three latent factors, updating, shifting and inhibition, and eight observed variables (see Figure 3). Digit Span Backwards was removed from the model as the factor loading (0.05) was not significantly contributing to the model (p = .54). The model was assessed using maximum likelihood. The measurement model showed an acceptable fit to the data, χ^2 = 26.10, df = 17 p = 0.07, CFI = 0.97, TLI = 0.95, RMSEA = 0.05 [90% CI: 0.00–0.09], SRMR = 0.04. In addition, all the factor loadings were significant, $p < 0.001$, and ranged from 0.231 – 0.873. These results indicate that the eight manifest variables well exemplified the latent factors. This model was then used to test the hypothetical structural model.

The SEM was verified using a maximum likelihood estimation. This model also showed an acceptable fit, χ^2 = 66.38, df = 51, p = 0.07, CFI = 0.95, TLI = 0.93, RMSEA

= 0.04 [90% CI: 0.00–0.06], SRMR = 0.05. There was no significant ($p > .05$) direct effect of age, physical activity, concussion history or athletic status in this model. Sex was a significant predictor for the factor, inhibition, $b = 0.52$, $\beta = 0.19$, $p = 0.02$, such that male participants had greater inhibition. Lastly and unsurprisingly, the two variables, physical activity and athletic status, were significantly correlated, $r = 0.33$, $p < 0.01$. These results are summarized in Figure 4.

Multiple Regression

A multiple linear regression was first calculated to predict scores on the EFI using age, sex, concussion history, physical activity and athletic status. The regression was significant, $F(5, 239) = 4.57$, $p < 0.01$, with an R^2 of 0.09. Age and sex were not significant predictors. Physical activity was a significant predictor of EFI scores, $b = 0.09$, $p < .01$. Thus, greater physical activity was associated with greater EFI scores. Concussion history was also a significant predictor, $b = 3.29$, $p < .05$, such that no history of concussion was significantly associated with higher EFI scores. Lastly, athletic status was a significant predictor, $b = -4.01$, $p < .05$, such that being a non-athlete was negatively associated with EFI scores. These results are further summarized in Table 4.

Considering the significant results of the full EFI scale, five follow-up multiple regressions were conducted for each of the subscales. For the MD subscale, the regression was significant, $F(5, 241) = 4.57$, $p < .01$, with an R^2 of 0.146. Age and concussion history were not significant predictors. Physical activity was a significant predictor of MD scores, $b = 0.02$, $p < .01$. Sex was also a significant predictor, $b = 1.17$, $p < .05$, such that male participants had significantly higher MD scores. Lastly, athletic status was a significant predictor, $b = -1.64$, $p < .01$, such that being a non-athlete was negatively associated with MD scores. The regression for the IC subscale was also significant, $F(5, 241) = 2.82$, $p = .017$, with an R^2 of 0.055. All predictor variables were insignificant, except for concussion history, $b = 1.46$, $p < .01$. Thus, those with no history of concussion had greater scores on the IC subscale. For the ORG, SP and EM subscales, the regressions were insignificant (ORG: $F(5, 241) = 1.11$, $p = .36$; SP: $F(5, 241) = 1.49$, $p = .19$; EM: $F(5, 241) = 1.21$, $p = .30$). For the ORG subscale, concussion history was a significant predictor, $b = 1.17$, $p < .05$, such that those with no history of concussions had greater ORG scores, although it only accounted for 1.00% of the variance. Additionally, sex was a significant predictor for the EM subscale, $b = -1.18$, $p < .01$, such that male participants had lower scores than their female counterparts, although it only accounted for 3.61% of the variance. The results of these regressions are shown in Table 5.

Discussion

To our knowledge, this is the first study to investigate the joint effects of physical activity, concussion history and athletic status on EF with both objective and subjective measures of EF. Further, we attempted to use these variables to predict not only the three latent factors of EF but also a self-report measure of EF. One of the strengths of this study was the robustness of the measurement of EF, as we used a multi-method approach for the assessment of three lower-order EF processes with multiple computerized tasks, in addition to a behavioural self-report of EF including five subscales, and the use of a latent variable approach to diminish task impurity issues. Few studies have done such a thorough assessment of EF and provide us with the opportunity for an in-depth investigation of the differences based on physical activity, concussion history and athletic status. Self-report measures may allow for more nuance within the behavioural manifestations of EF, which have important implications considering that self-report measures relate to everyday life much more than objective computerized tasks. The benefits of exercise and sport on subjective executive functioning has yet to be reported and can be utilized in future interventions and training to promote both exercise and cognitive functioning. Further, it is important to note that concussion history was negatively related to subjective executive functioning, with no apparent objective differences in performance, which aligns with previous research finding subjective deficits with no objective correlates (Schiehser et al., 2011).

While we hypothesized that greater physical activity levels and athletic status would predict better performance on objective, computerized measures of EF, this hypothesis was not supported by our findings. We also hypothesized that concussion history would be negatively associated with EF performance which was also not supported. However, these hypotheses were supported for our behavioural, subjective measure of EF, such that physical activity and no history of concussions were positively related to EFI scores while being a non-athlete was negatively associated with EFI scores. Thus, some of our hypotheses did receive support, but only for the behavioural subjective measure of EF that includes organization, impulse control, empathy, motivational drive and strategic planning and not the latent factors of EF, shifting, updating and inhibition. Further, while we did predict that the relationship between physical activity, athletic status and concussion history will be more pronounced for the self-report measure than the performance measures, this was not the case. However, these findings align with previous research that demonstrated performance-based measures of EF often do not align with self-report measures of EF which suggests they are complementary measures but may measure slightly different aspects of the underlying EF construct (Toplak et al., 2013; Isquith et al., 2013; McAuley et al., 2010). Thus, we discuss our findings in the context of objective, performance-based measures of EF and the subjective, self-report measure of EF.

Objective Executive Functioning

The results of the SEM indicated an overall good model fit with the three latent factors of EF, shifting, updating and inhibition, which provides further support for Miyake and colleagues' (2000) three-factor model when tested using different tasks used than in the original model. Interestingly, the correlations between the three factors in our study (i.e., 0.67, 0.77, and 0.82) were much higher than in the original Miyake et al. (2000) model. This may be due to the similarity in variables (all proportion of correct responses except for Flanker RT difference) included in our model, whereas Miyake and colleagues (2000) used differing types of variables for each latent factor. It may also be due to the conceptual overlap between tasks and the notion of ‘task impurity’’ in which it is hard to create a pure one-factor task, and instead, each task may be primarily one EF but still engages the other two as well. Further, some researchers posit that executive functioning may be better explained by one common higher-order EF (Friedman et al., 2008). However, due to the plethora of studies using a three-factor model and our unsuccessful attempt at a nested bifactor model, we aimed to predict the three factors, inhibition, shifting and updating with the variables, age, sex, concussion history, physical activity, and athletic status. This endeavour was largely unsuccessful, with only sex predicting inhibition.

The only significant predictor in the model was sex, such that males had greater inhibition than females. This result seems to support the concept of a male advantage in response inhibition found by previous researchers (Evans & Hampson, 2015; Stoet, 2010). However, other studies have found the opposite, with females having better inhibition than males (Sjoberg & Cole, 2018). A recent meta-analysis concluded that men and women did not differ in response inhibition (Gaillard et al., 2021a). Even more recently, though, Gaillard and colleagues (2021b) conducted a systematic review investigating sex differences in the neural networks of EF and determined that there are sex-specific strategies used that are task-dependent. For example, sex differences were found in the activation of the middle frontal gyrus, the superior frontal gyrus, the orbitofrontal cortex, and the inferior frontal gyrus during inhibition tasks (Gaillard et al., 2021b). Another interesting potential explanation for the inconsistency in sex differences may be due to women's menstrual cycle phase, as one study determined that women's performance on inhibition tasks differed depending on their menstrual cycle phase (Colzato et al., 2010). Relatedly, sex differences may be due to gonadal hormones such as testosterone, which has been found to enhance spatial working memory in men but the mechanism and effects on other EFs such as inhibition are still unknown (Gaillard et al., 2021a). Considering the mixed results and lack of definitive reasoning, future research should continue to explore the potential mechanisms and explanations for any observed sex differences in executive functioning.

Subjective Executive Functioning

Physical Activity

The results supported our hypotheses and the extant literature regarding a positive relationship between physical activity and EF. Specifically, physical activity was found to be significantly positively associated with overall EFI scores as well as the MD subscale. While previous research has demonstrated benefits of physical activity on objective EF tasks, less research has investigated the effects of physical activity on subjective executive functioning. Thus, these results provide further support for the benefits of physical activity on subjective cognitive functioning. Further, the most benefits may be through the effects of physical activity on MD, since physical activity accounted for 7.3% of the total 14.6% variance explained by the included predictors within the MD subscale. Considering MD is defined as ‘behavioral drive, activity level, and interest in novelty’ (Spinella, 2005, p. 660) and contains items such as “I have a lot of enthusiasm to do things” and “I tend to be an energetic person", it is logical that there is a relationship between physical activity and scores on the MD subscale. A further potential explanation for this relationship may relate to the personality traits, extraversion (e.g., enthusiastic, outgoing, and social), and conscientious (e.g., dutiful, self-disciplined; Costa & McCrae, 1995), as the items of the EFI’s MD subscale relate to enthusiasm, energy and drive. Previous research has determined that conscientiousness has a small effect on physical activity while extraversion has a small-to-medium effect (Rhodes & Boudreau, 2017; Rhodes & Pfaeffli, 2012). Perhaps the items from the MD subscale also relate to these personality traits that help explain one’s capacity to engage in physical activity. Thus, there appears to be a unique and significant relationship between physical activity and subjective executive functioning, particularly motivational drive, which may be related to individual difference that warrants future research.

Athletic Status

Similar to the positive effects of physical activity, athletic status was also a significant variable in the regressions. We determined that identifying as a non-athlete was negatively associated with EFI scores on the overall EFI and the MD subscale. Previous research also supported these results that determined that athletes tend to have superior executive functioning (Jacobson & Matthaeus, 2014; Yu & Liu, 2020). The results from this study are interesting, though, because athletic status was determined very liberally in that if someone played in a high school or community league (or a higher level) at any time in their life, they were identified as an athlete. Participants were only labelled a non-athlete if they reported never having played a sport or below the high school level (e.g., in middle school or elementary school). Recently, Koch and Krenn (2021) determined that past involvement in open-skilled sports (e.g., sports with a continuously changing environment such as soccer) is significantly related to EF, especially if one now plays closed sports (e.g., self-paced with a static environment such as running). They determined the nature of involvement in open-skill sports through retrospective interviews focused on sports involvement until the age of eighteen (Koch & Krenn, 2021). Thus, having been an athlete at any point in one's life seems beneficial to one's subjective executive functioning. In addition to overall subjective EF, athletic status was significantly related to the MD subscale, accounting for 6.8% of the total variance. Similar to physical activity, it is logical that being an athlete would be related to MD as research has shown that athletes tend to be more motivated than non-athletes across many facets of life, including physical activity, social and family life and competition (Reiss et al., 2001; Martindale et al., 1990). Thus, athletic status may play an important role in one's self-reported executive functioning and MD, specifically.

Concussion History

The results of the regressions indicated that no concussion history was significantly positively related to overall subjective executive functioning. Concussion history was also significantly associated with two subscales, IC and ORG. These findings are also not surprising, considering many people report issues with organization and impulse control following a concussion (Clarke et al., 2012; Miller & Leathem, 2016). While EF deficits are common after an acute concussion or traumatic brain injury, the deficits tend to resolve within a few weeks but, in some cases, can linger for months or even years (Webb et al., 2018; Ayala & Heath, 2020; Heitger et al., 2007). The reasoning for long-lasting EF deficits following a concussion is less understood. Further, previous research has shown that those in a semi-acute stage of recovery (less than three months post-injury) self-report executive dysfunction, even in the absence of objective measures of executive dysfunction (Schiehser et al., 2011). A potential explanation for this discrepancy between subjective and objective executive dysfunction is that the objective EF measures may not be sensitive to identify slight deficits in EF (Hanna-Pladdy, 2007; Hartikainen et al., 2009). Highly specific computerized tasks that assess particular EF processes such as inhibition or updating of working memory are very different from the demands of real life with all of life's novelty and complexity in which we engage and integrate multiple cognitive processes simultaneously. Therefore, slight deficits in EF may not be captured by our traditional computerized tasks and are instead better captured through self-report measures like the EFI.

Demographics

Age and sex were not found to be significantly associated with overall subjective executive functioning. While this is contradictory to previous findings with age being positively related to EFI scores (Spinella, 2005; King et al., 2018), it may be due to the small age range of our sample (18 - 25 years old), considering previous studies were examining participants across the lifespan. Further, previous studies have found that female participants tend to score higher than male participants, which was not supported by our findings. However, males had significantly lower scores for the empathy subscale, which aligns with previous research (Spinella, 2005; King et al., 2018). This lack of sex differences for the overall EFI scale may be due to our primarily female sample. In a study with a similar sample (primarily Female university students), researchers validated a Dutch version of the EFI and failed to find a significant effect of gender (Janssen et al., 2009). From the results of our study, age and sex do not appear to be significant to one's executive functioning, but this may be a result of our sample as it does not align with most previous research.

Limitations

This study is not without its limitations. Due to the entirely online nature of the study, participants may not have been fully engaged or motivated during testing. Similarly, there is no way to ensure all participants have the same computerized testing experience due to the participants using their personal devices (i.e., laptops versus desktop computers). This remote testing may have led to the univariate outliers (13% of original sample) we had to remove. However, once the outliers were removed, all the variables were normally distributed. Another limitation is that we only included two indicators for the updating factor; it would have been ideal to have three indicators for each factor, although the model still had an acceptable fit. Another possible limitation is that our predictor variables, athletic status, concussion history and weekly physical activity, were all self-report measures and, thus, may not have been as accurate as if they were objectively measured or reported. Lastly, due to the recruitment through psychology classes from the local university, our sample is primarily female and highly active, which may not be representative of the average university student population. This university sample may explain why some of the subscales such as Strategic Planning and Organization were not significant due to the potential lack of variability as strong planning and organization skills may be a prerequisite to successful performance in university.

Future Directions

This study provides many avenues for future research. First, it would be ideal for researchers in the future to attempt to replicate our findings in a controlled laboratory environment as participants completed the study remotely, and we cannot be sure of their level of focus. However, previous research comparing online, remote testing to in-lab testing have had positive results with no notable differences in performance (Hansen et al., 2020, Backx et al., 2020, Casler et al., 2013, Kim et al., 2019). Considering the global COVID-19 pandemic and the shift to more online methods of interaction, remote psychological research is likely to continue to occur, and this study serves as proof of concept of the types of studies that can be conducted fully remotely. Second, researchers should continue to investigate not only athletic status but also sport type to determine if there are unique differences in both subjective and objective EF dependent on the type of sport. Third, considering the significance of self-reported weekly physical activity on behavioural reports of EF, it will be necessary to follow up this finding with more objective measures of physical activity (e.g., wearable personal fitness tracker). Lastly, although we attempted to extract a Common EF factor using a nested, bifactor approach and were unsuccessful, it would be interesting to investigate if physical activity, athletic status, and concussion history are better predictive of Common EF than an individual EF.

Conclusions

This study examined the relationship between physical activity, concussion history, athletic status, age, sex and both subjective and objective measures of EF through a unique online assessment. While none of our hypotheses were supported for predicting objective measures of EF, we discovered some interesting results regarding sex differences that require more attention in the future. We also determined support for the positive effects of physical activity and sport participation on subjective EF, an area previously unstudied. Overall, these findings provide an interesting perspective on the relationship (or lack thereof) between predicting subjective and objective measures of EF with physical activity, sport and concussion history. Considering the diversity in EF measurement, these findings require follow-up studies to better understand the differences and similarities, especially in the context of physical activity and sports research on EF.

Tables

Table 1. *Means, standard deviations, skewness and kurtosis for EF variables used in the SEM analysis.*

Variable	*M*	*SD*	Skewness	Kurtosis
1. WCST	0.62	0.09	-0.20	-0.12
2. Alternate Task Switching	1.32	0.15	-0.98	1.56
3. Cued Task Switching	1.30	0.16	-1.3	2.79
4. Reading Span	0.49	0.20	-1.02	0.04
5. N-Back	0.82	0.11	1.1	0.17
6. Digit Span Backwards	0.41	0.24	0.75	-0.15
7. Flanker RT	-0.05	0.03	-1.23	1.56
8. Simon	0.91	0.05	-.89	0.76
9. Stop-Signal	0.74	0.14	-0.66	-0.36

Note. All variables except Flanker RT are proportions of correct responses. *M* and *SD* are used to represent mean and standard deviation, respectively.

Table 2. *Means, standard deviations, and correlations with confidence intervals of EF variables*

Variable	*M*	*SD*	1	2	3	4	5	6	7	8
1. Stop-Signal	0.74	0.14								
2. Flanker	-0.05	0.03	.19** [.06, .31]							
3. Simon	0.91	0.05	.36** [.24, .47]	.30** [.18, .42]						
4. N-Back	0.82	0.11	.39** [.27, .50]	.17* [.04, .30]	.25** [.12, .37]					
5. Reading Span	0.49	0.20	.09 [-.04, .23]	.20** [.07, .32]	.14* [.00, .26]	.16* [.03, .29]				
6. CTS	1.30	0.16	.47** [.36, .57]	.16* [.03, .29]	.24** [.11, .36]	.49** [.38, .59]	.15* [.02, .28]			
7. WCST	0.62	0.09	.22** [.09, .35]	.14* [.00, .26]	.10 [-.04, .23]	.18** [.05, .31]	.07 [-.07, .20]	.23** [.09, .35]		
8. ATS	1.32	0.15	.25** [.12, .37]	.15* [.02, .28]	.23** [.10, .35]	.39** [.27, .50]	.12 [-.02, .25]	.59** [.49, .67]	.21** [.08, .33]	
9. DSB	0.41	0.24	.14* [.00, .27]	.16* [.03, .29]	.05 [-.08, .18]	-.00 [-.14, .13]	.13 [-.00, .26]	-.03 [-.16, .10]	.14* [.01, .27]	-.03 [-.17, .10]

Note. Values in square brackets indicate the 95% confidence interval for each correlation. The confidence interval is a plausible range of population correlations that could have caused the sample correlation (Cumming, 2014). * indicates $p < .05$. ** indicates $p < .01$.

Table 3. *Regression results using total scores on the EFI as the criterion*

Predictor	*b*	*b* 95% CI [LL, UL]	*beta*	*beta* 95% CI [LL, UL]	sr^2	sr^2 95% CI [LL, UL]	*r*	Fit
(Intercept)	90.99**	[76.45, 105.54]						
Age	0.04	[-0.66, 0.74]	0.01	[-0.12, 0.13]	.00	[-.00, .00]	.00	
Sex (Male)	-2.43	[-5.92, 1.06]	-0.09	[-0.21, 0.04]	.01	[-.01, .03]	-.04	
Physical Activity	0.09**	[0.04, 0.14]	0.22	[0.09, 0.34]	.05	[-.00, .10]	.23**	
Concussion History (None)	3.29*	[0.27, 6.32]	0.13	[0.01, 0.26]	.02	[-.01, .05]	.10	
Athletic Status (Non-athlete)	-4.01*	[-7.78, -0.24]	-0.13	[-0.26, -0.01]	.02	[-.01, .05]	-.15*	
								R^2 = .087** 95% CI[.02,.14]

Note. Males are the reference group for sex; no concussion history was the reference group for concussion history; non-athlete was the reference group for athletic status. A significant *b*-weight indicates that the beta-weight and semi-partial correlation are also significant. *b* represents unstandardized regression weights. *beta* indicates the standardized regression weights. sr^2 represents the semi-partial correlation squared. *r* represents the zero-order correlation. *LL* and *UL* indicate the lower and upper limits of a confidence interval, respectively. * indicates $p < .05$. ** indicates $p < .01$.

Table 4. *Regression results for all five subscales of the EFI*

Subscale	Predictor	*b*	*b* 95% CI [LL, UL]	*beta*	*beta* 95% CI [LL, UL]	sr^2	sr^2 95% CI [LL, UL]	*r*	Fit
Motivational Drive (MD)	(Intercept)	13.88**	[10.13, 17.62]						
	Age	-0.00	[-0.19, 0.18]	-0.00	[-0.12, 0.12]	.00	[-.00, .00]	-.03	
	Sex (Male)	1.17*	[0.27, 2.07]	0.15	[0.04, 0.27]	.02	[-.01, .06]	.17**	
	Physical Activity	0.02**	[0.01, 0.03]	0.23	[0.11, 0.35]	.05	[-.00, .10]	.27**	
	Concussion History (None)	-0.42	[-1.21, 0.36]	-0.06	[-0.18, 0.05]	.00	[-.01, .02]	-.10	
	Athletic Status (Non-athlete)	-1.64**	[-2.62, -0.67]	-0.20	[-0.32, -0.08]	.04	[-.01, .08]	-.26**	R^2 = .146** 95% CI[.06,.21]
Organization (ORG)	(Intercept)	14.89**	[9.56, 20.22]						
	Age	-0.03	[-0.29, 0.23]	-0.02	[-0.14, 0.11]	.00	[-.00, .00]	-.01	
	Sex (Male)	-0.17	[-1.46, 1.11]	-0.02	[-0.14, 0.11]	.00	[-.00, .00]	.00	
	Physical Activity	0.01	[-0.01, 0.02]	0.06	[-0.07, 0.19]	.00	[-.01, .02]	.06	
	Concussion History (None)	1.17*	[0.05, 2.28]	0.13	[0.01, 0.26]	.02	[-.01, .05]	.12	
	Athletic Status (Non-	-0.62	[-2.00, 0.77]	-	[-0.19,	.00	[-.01, .02]	-.05	R^2 = .022

	athlete)			0.06	0.07]				
									95% CI[.00,.05]
Strategic Planning (SP)	(Intercept)	26.49**	[21.38, 31.60]						
	Age	-0.08	[-0.33, 0.17]	-0.04	[-0.17, 0.09]	.00	[-.01, .01]	-.04	
	Sex (Male)	-1.07	[-2.30, 0.16]	-0.11	[-0.24, 0.02]	.01	[-.01, .04]	-.10	
	Physical Activity	0.01	[-0.00, 0.02]	0.11	[-0.02, 0.24]	.01	[-.01, .04]	.11	
	Concussion History (None)	0.64	[-0.43, 1.71]	0.08	[-0.05, 0.20]	.01	[-.01, .02]	.05	
	Athletic Status (Non-athlete)	-0.44	[-1.77, 0.88]	-0.04	[-0.17, 0.08]	.00	[-.01, .01]	-.05	R^2 = .030
									95% CI[.00,.06]
Impulse Control (IC)	(Intercept)	13.78**	[9.29, 18.27]						
	Age	0.11	[-0.11, 0.32]	0.06	[-0.06, 0.18]	.00	[-.01, .02]	.08	
	Sex (Male)	-0.96	[-2.04, 0.12]	-0.11	[-0.23, 0.01]	.01	[-.01, .04]	-.09	
	Physical Activity	-0.00	[-0.01, 0.01]	-0.03	[-0.16, 0.09]	.00	[-.01, .01]	-.06	
	Concussion History (None)	1.46**	[0.52, 2.40]	0.20	[0.07, 0.32]	.04	[-.01, .08]	.19**	
	Athletic Status (Non-athlete)	0.01	[-1.16, 1.18]	0.00	[-0.12, 0.13]	.00	[-.00, .00]	.04	

									R^2 =. 055* 95% CI[.00,.10]
Empathy (EM)	(Intercept)	23.83**	[19.08, 28.58]						
	Age	0.09	[-0.14, 0.32]	0.05	[-0.07, 0.18]	.00	[-.01, .02]	.05	
	Sex (Male)	-1.18*	[-2.33, -0.04]	-0.13	[-0.26, -0.00]	.02	[-.01, .05]	-.12	
	Physical Activity	0.00	[-0.01, 0.01]	0.02	[-0.10, 0.15]	.00	[-.01, .01]	.03	
	Concussion History (None)	0.20	[-0.80, 1.19]	0.03	[-0.10, 0.15]	.00	[-.01, .01]	.01	
	Athletic Status (Non-athlete)	-0.75	[-1.98, 0.48]	-0.08	[-0.21, 0.05]	.01	[-.01, .02]	-.07	R^2 = .024 95% CI[.00,.05]

Note. Males are the reference group for sex; no concussion history was the reference group for concussion history; non-athlete was the reference group for athletic status. A significant *b*-weight indicates that the beta-weight and semi-partial correlation are also significant. *b* represents unstandardized regression weights. *beta* indicates the standardized regression weights. sr^2 represents the semi-partial correlation squared. *r* represents the zero-order correlation. *LL* and *UL* indicate the lower and upper limits of a confidence interval, respectively.
* indicates $p < .05$. ** indicates $p < .01$.

Figures

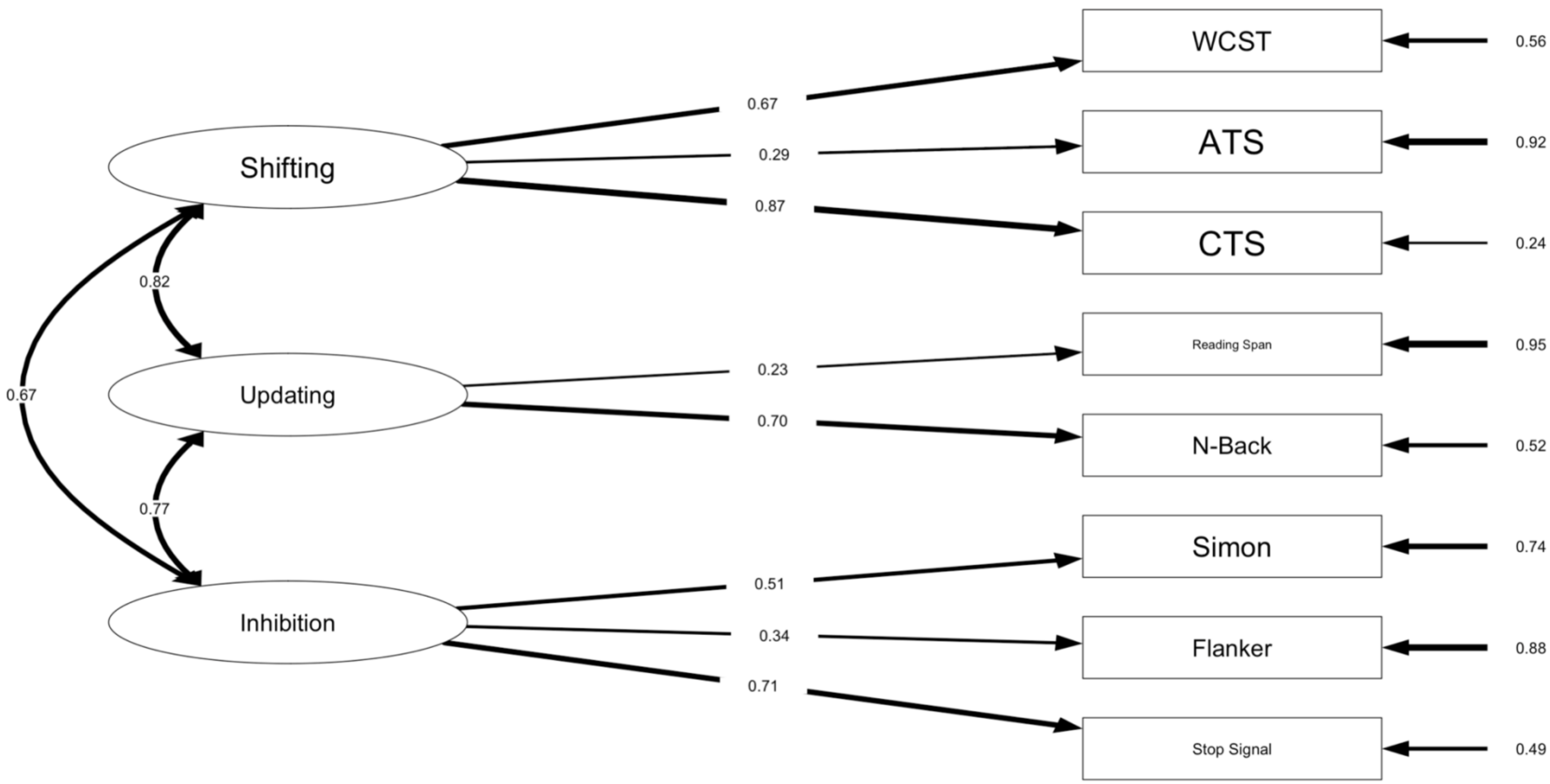

Figure 3. CFA model of the three latent factors of EF with eight indicators.

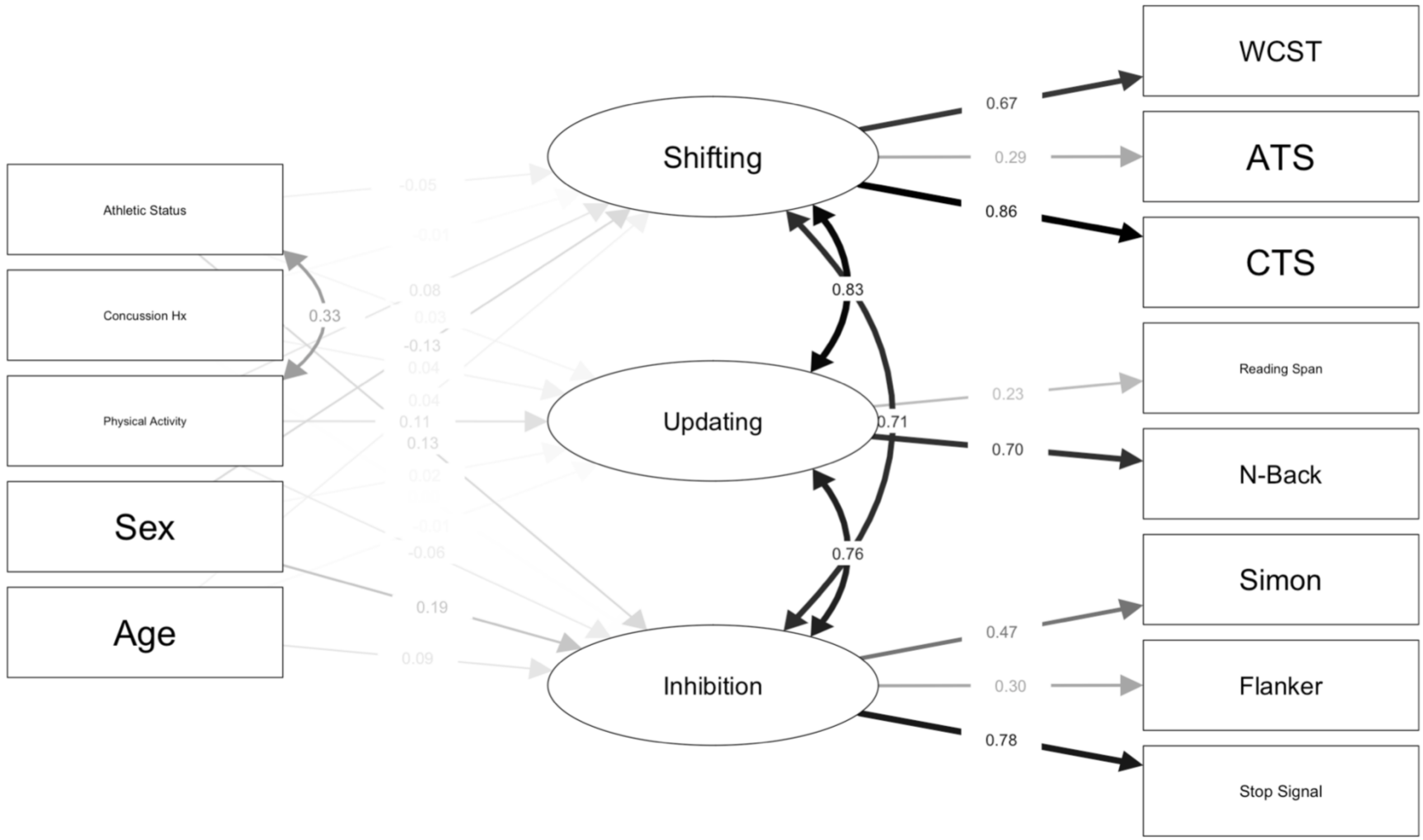

Figure 4. Structural Equation Model of EF.
Note. The thicker and bolder the line signifies the greater the factor loading.

Chapter 3: A Qualitative Investigation of Executive Function in Externally Paced Sport within *"The Structure and Chaos of the Game"*

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Author Note

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Abstract

Introduction: While previous quantitative research has determined that executive function is malleable to sport participation, executive functioning in sport has not yet been investigated qualitatively in elite university athletes' sport experiences. Understanding the executive processes used in sports from an athletes ' perspective is vital to create more pertinent assessments as well as to provide accessible, athlete-focused language to describe executive function in sport. Therefore, our study had the following research question: 'What is the role of executive function in elite sports athletes' sport experiences?'.

Methods: 19 Canadian U-Sports athletes (ages 18 – 25; 37% female) were recruited through emailing coaches and social media. The participants completed semi-structured interviews via Zoom with a focus on identifying their executive function processes in sport. Thematic analysis was used to analyze the interview transcripts.

Results: We generated three themes: 1) Engaging in pre-play or pre-game planning, organization and decision making, 2) Engaging in mid-play problem solving and purposive action and 3) Engaging in post-play or post-game information processing, emotional control and effective performance.

Conclusions: Our study determined that the executive functions athletes use are dependent on their involvement in the play and the point of the game (pre-, mid- or post-). The three themes demonstrate that throughout different moments of the game, the athletes engage in several executive functions such as planning (pre-), problem-solving (mid-), and self-monitoring (post-). These findings offer a unique contribution to our understanding of athletes' executive function in sport and have important implications for sports psychologists and related professionals assessing and explaining executive function to athletes in the future.

Keywords: sports, athletes, executive function, neuropsychology

Introduction

Athletes are always proactively and strategically planning their movements, quickly inhibiting actions that are no longer useful, and evaluating these actions to make necessary adjustments to achieve the desired result during a game. They are constantly solving problems, making decisions, and organizing plays. Therefore, athletes are constantly engaging their executive functioning while playing. Executive function (EF) can be generally considered a higher-order cognitive function that produces goal-directed behaviours in complex situations. As defined by Jurado and Rosselli (2007):

> In a constantly changing environment, executive abilities allow us to shift our mind set quickly and adapt to diverse situations while at the same time inhibiting inappropriate behaviors. They enable us to create a plan, initiate its execution, and persevere on the task at hand until its completion. Executive functions mediate the ability to organize our thoughts in a goal directed way and are therefore essential for success in school and work situations, as well as everyday living (p.214).

Some models of EF may serve to explain this engagement of executive abilities in an athlete's sport practice.

Lezak et al.'s (2004) taxonomy of EF has four main components of EF: 1) volition (e.g., the process of deciding one's wants and needs then conceiving how to achieve them), 2) purposive action (e.g., employing an intention or plan through complex behaviour that may need to be sustained, adapted or inhibited in an organized and cohesive way), 3) planning and decision making, and 4) effective performance (e.g., one's capacity to monitor, self-correct, and regulate their performance). We speculate that athletes may be engaging in all four of these components when they are playing. They may engage volition when they decide their wants and needs within the game and then determine how best to achieve them. They may engage in purposive action throughout the game as they employ their intentions determined through their volition and adapt, inhibit or sustain the needed actions. They seem to be planning moves and plays and then making decisions based on different contingencies. Lastly, they may engage in effective performance when they are regulating, adapting and tracking their performance throughout the game.

Not only do athletes seem to be monitoring their performance and making decisions throughout the game, but we propose they are constantly problem solving, whether it is a 'big' problem such as trying to tie up a 1 - 0 game or a 'small' problem such as trying to make a tough pass between two opposing players. Zelazo and colleagues (1997) use a problem-solving framework approach to EF with four stages: 1) problem representation, 2) planning, 3) execution and 4) evaluation. We believe that athletes follow these four stages rapidly during the game. For example, a soccer player is trying to beat a defender one-on-one to try and score a goal. First, the player identifies the problem: the looming defender ahead who is trying to stop them from scoring (problem representation). Second, the player plans what they need to do, thinking of alternative actions and deciding on their desired plan, a specific move to beat the defender (planning). Third, they execute this intended move in an attempt to beat the defender (execution). Fourth, the player quickly evaluates if they were successful in beating the defender and scoring (evaluation).

Both Lezak et al.'s (2004) and Zelazo et al.'s (1997) conceptualization frameworks are integrated and based on real-life behaviour instead of specific, lower-order EF processes, such as inhibition. However, researchers rarely use these conceptualization frameworks to operationalize EF, instead often preferring latent factor approaches that are easy to assess with cognitive tasks (Miyake et al., 2000; Karr et al., 2018). Moreover, past research has primarily focused on quantitative methods of evaluating EF in sport and has neglected to utilize a qualitative approach.

Current quantitative research has shown that EF may be malleable to specific environmental, cultural and lifestyle factors, including exercise and sport (Vrinceanu et al., 2018; Jacobson & Matthaeus, 2014; Hall et al., 2001). Not surprisingly, studies have focused on examining the potential EF advantage in athletes (Ballester et al., 2019; Chueh et al., 2017; Verburgh, 2014; Vestberg, 2012). Not only have researchers been broadly investigating the effects of sport on EF, but there has also been continued research investigating differences based on sport type to see if there are differential gains. Sports can be differentiated into externally paced (EP) sports and self-paced (SP) sports. Externally paced (EP) or open skill (OS) sports such as tennis or team ball games are sports in which the environment controls the rate of performance, while self-paced (SP) or closed skill (CS) sports such as swimming or track and field are sports in which the athlete controls the rate of performance (Singer, 2000). Due to the dynamic and unpredictable nature of EP sports, EP athletes tend to perform better on specific EF measures, including problem-solving and inhibition, in comparison to SP athletes and nonathletes (Jacobson & Matthaeus, 2014; Ballester et al., 2019; Zhu et al., 2020). Thus, athletes playing EP sports may be a particularly fitting population to better understand the EF processes during a game that is always changing and evolving.

The intricacies and complexities of executive functioning in sport have not yet been investigated qualitatively in elite EP athletes' experiences of sport. In fact, there is a scarcity of qualitative research exploring EF in athletes which may provide more nuance and insight into these complex, integrated processes that are used in everyday life. Related to EF, however, previous qualitative research has explored the interplay between motivation and self-regulation in five elite female athletes (Jordalen et al., 2020). They determined that planning and self-control were engaged following changes in motivation throughout their athletic careers, as well as engagement in self-control and self-reflection in extrinsically motivated athletes (Jordalen et al., 2020). Another study interviewed eight elite trampoline athletes to break down the meaningful actions and units of performance (Huaw & Durand, 2004). Huaw and Durand (2004) determined that when exercises were labelled 'average', the athletes felt in control of their actions, and this was deemed 'regulating the situation'. When the athletes performed an exercise labelled 'very good', it was deemed 'attentive monitoring' and the athletes described feeling advanced and were closely monitoring their actions. While both previously mentioned studies do not explicitly use the conceptualization of EF in their interpretation of results, there are many conceptual similarities in their findings to EF processes including regulating, monitoring and evaluating. Even with these related findings, however, to our knowledge, no qualitative study has ever directly explored EF in sport.

As intuitive as it sounds, no one has yet asked athletes themselves to describe their thought processes for researchers to better understand 'what is executive about their game?' and the best way to capture this information is through interviewing the athletes. So, recognizing athletes' perspectives is essential to deepen our understanding of how athletes utilize their executive functioning while playing. It will also provide more athlete-focused language and information to help assess and explain EF in sport in the future. Considering that the construct of EF does not translate into everyday language as easily as 'memory' or 'attention,' there is a need for a more accessible understanding of EF in sport. Further, elite EP athletes, while likely unaware of the intricate theoretical concepts of EF, use them every time they engage in their sport and are thus, a fitting population for this study. Therefore, this study aims to understand EF from an EP athletes' perspective. With this purpose in mind, we aim to address the following research question: 'What is the role of EF in elite EP sports athletes' experiences of the game?'.

Materials and Methods

Philosophical Assumptions

This study adheres to a relativist ontology which means that we consider "social reality as humanly constructed, multiple and subjective" (Smith & Caddick, 2012, p.61). Methods aligning with a relativist ontology include interviews based on participants' reconstructed experiences of past events in conjunction with the researcher's interpretations of these experiences (Guba & Lincoln, 2005). This analysis, therefore, aims to provide an interpretative understanding of the EF gained through the interactions with the participants (Guba & Lincoln, 2005).

This study falls within a post-positivistic epistemology, which claims objectivity and value-free inquiry are unattainable in scientific research. Further, it claims that both quantitative and qualitative methods are needed as both are imperfect (Patton, 2015). Therefore, a post-positivism epistemology is a suitable philosophical position that will guide the thematic analysis to understand EF in sport that has been previously studied using quantitative methods.

Participants

Purposive sampling was used to recruit EP athletes playing Canadian U-Sports aged 18 – 25 years old with a history of concussion within the last five years. This study was part of the Sport and Concussion Research on Executive System (SCoRES) project which had two main focuses: 1) EF and athletes’ experiences of sport and 2) athletes’ experiences of concussion. While it was important to have a sample with SRC history for the secondary study on concussion experiences, EP athletes tend to have high rates of concussion due to the nature of their sports (Kerr et al., 2017) and therefore, we believe that SRC history was not an unlikely or distinguishing feature for our study focusing on athletes’ EF and their experiences of sport.

Participants were recruited through emailing coaches of Canadian U-Sports Men's and Women's EP teams (i.e., rugby, field hockey, basketball, and soccer) at the local university. We also recruited U-Sports athletes from other universities through social media platforms (e.g., Twitter and Instagram) and targeted Facebook Ads.

Of the initial 26 athletes who expressed interest in the study, two did not follow-up to schedule an interview, one did not meet the age requirement (between 18 and 25 years old), and four did not have any SRC history. Thus, 19 participants completed the interview process. The participants ranged from 18 to 25 years old, with an average age of 21.74 (SD = 2.13). The athletes were 37% female; they primarily identified as white, except one participant was half-Indigenous, and one did not specify. The athletes came from four EP sports teams including soccer (n = 8), rugby (n = 6), volleyball (n = 3) and basketball ($n = 2$). More details, including pseudonyms for each participant, are shown in Table 5.

Procedure

Semi-structured interviews were used and chosen for several reasons. According to Vivar et al. (2011), there are four characteristics of semi-structured interviews that make them the best approach for this type of study. First, this method allows us to gain subjective and narrative descriptions of EF. Second, in semi-structured interviews, participants are asked the same questions; thus, the data is more easily organized around areas of interest (e.g., decision making, problem solving). Third, there is more flexibility in comparison to a structured interview, allowing participants to express their thoughts and opinions more freely. Lastly, since the interviewer can ask for clarification, it enhances validity (Vivar et al., 2011).

Before conducting the interviews, ethics approval was received from the local university's human research ethics board (protocol #20-0497-02). Participants gave their informed consent prior to participating in the interviews and were informed before joining the interview that the session will be recorded with their consent. The interviews allowed athletes to provide in-depth information about how they think when playing their sport. The interview guide was first piloted with two elite-level athletes with a prior history of concussion to obtain feedback on the questions (e.g., unclear or vague). We also listened to the recording of these pilot interviews to check the questioning style and improved some of the wording of the questions (see Table 6 for interview questions). The interviews were conducted online via a secure institutional account for Zoom teleconferencing. Zoom was chosen for the online interviews as the data is not stored in a third-party server, and sessions can be locked and recorded; further, Zoom has been deemed to have acceptable security (Archibald et al., 2019). Participants were encouraged to use the video option to connect with the interviewer but were not required to do so.

Initially, to 'break the ice, ' athletes were asked to talk about their everyday lives as elite U-Sports athletes (Jordalen et al., 2020). Then, with an emphasis on EF concepts, athletes were asked about their sport and their development and maintenance of elite-level performances (e.g., "Tell me about the process of learning and developing a new skill or play in your sport"). Throughout the interview, athletes were guided to elaborate on their sporting experiences in the context of executive functioning (e.g., "Tell me about how you determine what play to make during a game?"). Additionally, follow-up questions and comments to prompt athletes' further elaboration were used (e.g., "Can you walk me through an example…?") and served to help athletes in their retrospective reflections. To ensure we did not bias the participants' responses, we did not explicitly use the term 'executive function' or provide them with any theoretical frameworks during the interview. The interviews lasted approximately 30 minutes. The design and methodology were created following the Consolidated Criteria for Reporting Qualitative Research (COREQ) 32-item checklist (Tong et al., 2007).

Data Analysis

A thematic analysis approach was used to detect, analyze, and interpret patterns and themes within the athletes' descriptions of EF (Smith & Caddick, 2012). Braun and Clarke's (2006) six-step procedure for thematic analysis was followed to prepare and analyze the data. First, familiarization with the data was done through transcribing interviews verbatim and re-reading through the transcripts. This familiarization and re-reading also ensure the accuracy of the transcriptions. Second, generation of the initial codes was completed by coding features of the data representing components of EF in a systematic way facilitated by the qualitative data analysis NVivo 12 software (QSR International Pty Ltd., 2020). Then, a theoretical thematic analysis was conducted with a focus on addressing the research question about EF in sport, and the data was analyzed with this research question in mind. Therefore, only data segments relevant to the research question were coded. Open-codes were used, so there were no predetermined codes but the codes were established and revised as needed throughout the analysis (Maguire & Delahunt, 2017). 41 initial unique codes were generated representing basic units of texts based on different components of EF (e.g., planning, inhibiting distractions, self-monitoring). Third, the organization of the codes were reviewed, and the latent themes based on the components of EF were determined. Fourth, a review of these latent themes led to the generation of a thematic 'map' of the analysis (see Figure 5). Fifth, the themes were defined and named with a focus on refining the specifics. Sixth, the findings which contain compelling examples from the athletes were summarized (Braun & Clarke, 2006).

Lastly, it is understood that the themes generated from the thematic analysis result from subjective coding, which is affected by the personal knowledge and experiences of the coder. Considering the first author conducted all the interviews and coding independently, she may have been biased due to her past personal experiences as a collegiate soccer player. However, qualitative analysis is inherently subjective. The first author’s previous experiences with sport increased her interest in the research question, and it allowed her to connect with the athletes and understand their descriptions of complicated plays and rules of the game. Therefore, it is our belief that her extensive experience in sports provided more nuanced and comprehensive detail from the athletes because they knew she understood and did not have to break down the basics of the game during the interview.

Results

Three themes regarding athletes' executive functioning in sport were generated through the thematic analysis: 1) Engaging in pre-play or pre-game planning, organization and decision making; 2) engaging in mid-play problem solving and purposive action; and 3) engaging in post-play or post-game information processing, emotional control and effective performance (see Figure 5). The temporal organization of these themes are best described by Elijah as he states,

> “When you're playing soccer, I would say that the biggest thing that comes to my mind is that it changes a lot. It totally depends on the exact situation in the game. Like my mindset before the kickoff versus when I have the ball versus when it's way on the other side of the field, it's all totally different… it totally depends on … each stage like little, small action commands versus more analytical mixed in with emotional checks.”

Engaging in pre-play or pre-game planning, organization and decision making

The athletes engaged in planning, organization, and decision-making either before the game or immediately before a play to prepare for their desired or intended action. Planning and organization, in particular, were evident in the pre-game preparation, often starting the night before. For example, as stated by Kylie, “most of my mental preparation was the night before. I would watch film, go over the scouting report…You'd have to have them memorized for shoot around the next day". The athletes often described watching their previous games or learning about the opposing team the night before to prepare. Further, Henry explains how he would plan his meals, "the night before I'd make sure to eat a lot of pasta or something carb heavy, a lot of rice … I always make sure I've eaten well the night before and during that day". Sometimes the planning and preparation for games "starts during the week, during training… taking care of the body and if there's any sort of niggly injuries, making sure you're taking care of them and making sure you're available for the game on the weekends" (James). All these tasks and activities the athletes engage in before their game emphasize a high level of planning; however, the athletes also discussed pre-game preparations in their everyday lives as student-athletes with a high level of organization. Sasha describes how she "usually ha[s] a little bag ready to go [with] my puffer, any sort of Tylenol I might need, A-535…" that she organizes before the game. Further, Mia explained how she has a "very structured day and I follow my routines to a tee. So, I have designated time for studying, designated [time] for working out…". The high level of organization that was apparent is crucial to success in the busy lives of student-athletes as they balance school, practices, workout sessions, and games.

In addition to pre-game preparations prior to the commencement of a game, the athletes discussed planning, organization and decision making during the game before being actively involved in a play. Planning was utilized to maximize success when the athletes were actively involved in the play as it provided them with a framework to know what to do:

> "When the ball is coming towards me, I would usually already have a plan in mind, like a pass that I want to play or a first touch that I want to take. If I'm feeling good about myself, then my plan will be somewhat more ambitious or something a little more creative and if I'm not super confident, then it'll just be something safe." (Nathan)

Cameron echoes this statement while playing volleyball but cautions that when playing, athletes need to be flexible with this plan,

> "It's kind of funny [be]cause you want to have a game plan before you make each play. So, have an idea of who's where, and what you want to do…you want to have a game plan, but not committed to stick to that game plan, you know? Because otherwise then you're just gonna end up screwing up, making a really bad set or a bad choice".

The athletes would also try to plan what play would come next, "Thinking about plays… if this happens, then I gotta do this. If this happens, then I got to use that. It's kind of like plan A, B and C, try and plan ahead." (Emma)**.** Olivia felt similarly, explaining that,

> "I don't just look at what's ahead of me… I'm thinking, what is two or three plays from now…what's happening after I do what I do… it impacts how I know where I'm going to set up afterwards, like anticipating the team... what's going to be happening afterwards… I think two or three plays in advance every time."

Thus, the athletes are planning each action strategically, often even multiple actions in advance before they even have the ball because once they have the ball, it is too fast paced to determine their actions at the moment.

Playing a team sport requires organization to maintain the team's structure and integrity that they have planned in practices and pre-game preparations. William describes the “puzzle pieces” that an athlete must piece together regarding where one’s teammates are and where the open space is. He likens it to "one giant math equation". Organization, in terms of positioning, was critical, "forming a defensive line in rugby if you're on defense, you want to be a flat line, but if you're attacking you want to be more diagonal” (Henry). Further, Mia, a soccer goalie, describes her role as primarily organizing her teammates:

> “When the ball is on one side of the field, I'm always looking at the other side too, and making sure that everyone is dropping [be]cause there's usually someone on the other side of the field just wide open, so most of my thoughts during the game [have] to do with positioning my team and the other team and then as well as organizing walls and plays like goal kicks.”

Therefore, employing high levels of organization was most beneficial before the play to enhance the ease of the play once the athletes have the ball.

One of the most discussed executive processes was the pre-play decision-making immediately before the athlete receives the ball. Since the moment in which the athlete has the ball is so fast paced, the decisions are made “when I don't have the ball” (Emma). There are many contingencies that an athlete quickly assesses before they produce the action or play they decided on, as explained by Sasha when she is playing soccer:

> “When did I recently play a long ball? How tired are our strikers and how can I play another long ball over their back line? Are they high up and can my strikers

> run to go get it? Are they in the position to do that? Are they thinking that I could play a ball along right now?"

As is the nature of EF, the decision-making process in sports is further dependent on the "constantly changing environment" (Jurado & Rosselli, 2007, p.214), including one's teammates, the other team, and the game's score. In terms of teammates, Olivia, a rugby player, discuss how it is dependent on the strengths and positions of their teammates:

> "Every position on the team does a little bit different thing…everybody has different strengths…if the other one of my position is next to me, I'm probably not prioritizing 'catch the ball' because they're probably not going to pass it to me that hard because we don't do a lot of passing in my position. If I'm next to somebody like a center or a ten, I'm probably focusing on something like 'catch the ball' because they're generally the players who have really strong catch-pass skills."

Executive decision making involves connections of the fronto-parietal network that are constantly integrating sensory information such as the characteristics of the other team, "I have a setter [on the other team], who's 5'2, I'm 6'0 tall… I can go over top of them…if I have a right side who's 6'2 … I don't want to try to swing straight into her hands." (Abby). Ultimately, most athletes have "a set of plays" that they can use throughout the game and what play they choose depends "on the situation…where we are on the field, what the personnel is like" (James) as well as "on the scenario…if you're one nothing down or if it's tied or it's late in the game" (Andrew). James expands on this by explaining, "each of those plays has different options that you can choose depending on what the other team shows you." Deciding their action before receiving the ball and considering their previous action, teammates, the other team, and the score increases the athletes' efficiency and the likelihood of a successful play.

Engaging in mid-play problem solving and purposive action

While actively involved in a play, an athletes' thought process is rapid to solve problems and produce, maintain, switch and inhibit actions needed for success, known as purposive action (Lezak et al., 2004). Problem-solving during a play is quick yet complex as the athletes employ many functions such as problem representation, planning, execution, and evaluation to arrive at a solution. Many of the athletes discussed solving problems mid-game, specifically problem representation, by weighing the “risk-reward” (Chris). It was also apparent that athletes solved problems by having options predetermined in the planning and preparation stage, like Sam, who discusses having "first, second, third, fourth options" that he "cycle[s] through…as quickly as possible". Further, William describes solving problems at the team level as part of “the structure and chaos of the game” as one tries to find solutions based on experience and tactics (e.g., structure) to mitigate the chaos. He further elaborates on how he solves problems at the individual level:

> “First, identify the problem… in this case it will be… two attackers coming against one defender. Stabilize the problem…if they're coming at you full speed, try and slow them in their tracks, delay their attack and then from that point, counter the problem… if there is ever an opportunity to take a guy away and pull it so it's now a one-on-one situation… the problem becomes smaller, or if you can cause a turnover, interception that kind of thing that works too…and then,

> resolution. Problem solving is all about coming to a solution. [The] solution for this would be to win the ball back [and] don't let them score…."

Almost instantaneously, the athletes identify a problem, either within their own play or within their team's play; they determine potential solutions, evaluate their options, and execute their chosen solution. In addition to solving problems during play, athletes engage in purposive action: updating, switching and inhibiting their thoughts and movements to produce the best actions needed for success.

In the moment-to-moment play, athletes quickly produce, sustain, and adapt their movements based on feedback from themselves, their teammates, and the game. Many factors determine one's actions once they receive the ball, even if they have a pre-planned and well-organized action decided prior to receiving the ball. Julian describes this in rugby when a play does not go as planned:

> "We make calls as we know what plays about to happen, but you don't know until you have the ball. It depends on what the other people do. It depends on how your pass is, how the ball is. [The] play was meant to come out straight, from hand to hand, a passing play, and it got messed up…the ball went over the person in between myself and the ball thrower. I've gotta catch and so I come over and immediately, my legs change position, [my] foot swaps to go towards the ball and then I try and analyze where it's going to bounce based on the shape of it …how it's coming and then moving my legs towards it… little peripheral vision view of where everybody is at that split second and then probably the last thought would be is it safe to hold the ball or do I need to get rid of it as fast as possible?"

The athletes often discussed being flexible and able to change their actions based on what the other team does: “what you're trying to do is make the defense make a decision and then based on the defense's decision, ideally, you have two options [from] the one decision that the defense [makes]... Like if you do this, then I'll do this” (James). Julian explains how he may change or maintain his actions based on the defence:

> “Right before I catch, I do a quick analysis if that play is still viable and if it is, I'll follow through [with] that play…But if based on their defense…, it's not viable anymore, then I'll take it upon myself to do something else.”

Sophia further explains that purposive action needs to be quick to be successful, “when you realize that [what] you've done…it’s not going to work…whatever your plan is, you have to be super, super quick …and usually the quicker you are… will make or break the play”. Even though most of the decision-making occurs before the athlete even has the ball, the athletes must analyze their surroundings and be flexible to change their planned actions if needed.

Engaging in post-play or post-game information processing, emotional control and effective performance

Athletes frequently described a difference in thought processes when they had finished the play or game because they have more time to process information and reflect on their actions. Once they are no longer actively involved in the play, athletes have a moment to think critically about the game and process all the information available to them, “I know the ball [is] on that half…[so I] take a step back and review how the game is going… It's like the tunnel vision goes away, and you can kind of see the forest for the trees’ (William). This reflection tends to occur when “the ball [is] really far away” or “out of play” (Elijah), which allows the player to have some time to ask questions such as, "what is [the other team's] shape? (Elijah) “What have I done in the past game that [has not] worked out super well for me? What can I change? (Emma). The athletes' questions highlight the cognitive evaluation and processing they are engaging in.

The athletes also recognize that while challenging to control their emotions, it is advantageous to attempt because if they let their emotions take over, they tend to play worse and make more mistakes. For example, Nathan emphasizes that “I really try to move on from whatever happened in the past. You can't change it, even if it's big mistake, though I find that way more easy to do in theory than in reality.” Athletes discussed using many strategies for emotional control after making a mistake or when they were not playing well, including 1) “Smiling… it'll really help [you] lessen the load and relax” (Cameron), 2) “Take your water bottle and have a check-in with yourself… One to ten, how am I feeling… with my gameplay, how am I managing my emotions on the court and then …leave it with your water bottle” (Abby), 3) “Take a breath and have a short memory, trying not to focus on the negatives and play what's in front of you” (James), 4) “Focus on one object on the field, focus on the grass or something for a few seconds… calm down” (Julian). However, the athletes acknowledge that controlling their emotions is complex. They may have moments where they question themselves before being able to control their frustration, “I drop the ball, and it's like what are you doing...you're letting people down... trying to just acknowledge how I'm feeling in the moment and then letting that pass” (James). Emotional control was described by the athletes to be an executive process that is vital to maintaining their performance and preventing mistakes.

In addition to controlling emotions during stoppages in play, halftime, timeouts or after the game, the athletes are also continuously evaluating and monitoring their play to produce better results in the future, known as effective performance (Lezak et al., 2004). For example, Elijah explains evaluating his performance, “During the [stoppage of play], one thing I do [is] I'll check in with myself… 10 minutes have gone by, what do I think...then I'll be like…I've been playing pretty well, I want to keep that going…". Sam also describes, “a dialogue of what's happening, processing what's going on in the game… feeling it out…knowing where everyone's positioned, where do you need to be positioned...figuring out the game”. Chris describes self-monitoring when explaining that he is “very much in tune with myself and my mind and how I'm playing" after each volleyball point. In addition to self-monitoring, the athletes are on team sports and, consequently, evaluate their play as part of a whole. For example, James explains that when the other team is winning in a rugby game, he and his team are:

> “Trying to see what they're doing that is beating us and how can we change? How can we change what we're doing to give ourselves the highest amount of success? We had to change on the fly the way we are defending our line outs. I tried to simplify it as much as possible because they were there beating us with a lot of movement. So, I said alright, we're going to pick a spot before the line out and we're going to go up there. We're going to wait for them to move, we’re going up there no matter what and we had more success in the second half of that game.”

Evaluating the game as a team was essential, as they worked together to discuss, “okay, this has happened, but what are we going to do and how are we going to move forward?”

(Abby). Lastly, William states, "For me, the ultimate thing that I always think about is how are we playing and are we playing well? Are we connected and are we going to win this game?" These evaluative thoughts are crucial for the athletes to continue playing at the optimal level throughout the game and the entire season.

Discussion

EF in sport has been extensively studied using quantitative methods, but it is less understood how athletes themselves may describe the EF processes they employ during the game. Introducing a qualitative aspect provides richness to our understanding of EF in sport by providing insight that scores on tasks or questionnaires cannot give. Our purpose was not to redefine EF but to explore the degree to which current frameworks of EF were also applicable to the sport context and explore possible important executive processes that may have been overlooked in traditional quantitative research. Through thematic analysis, we generated three themes: 1) Engaging in pre-play or pre-game planning, organization and decision making, 2) Engaging in mid-play problem solving and purposive action and 3) Engaging in post-play or post-game information processing, emotional control and effective performance. Thus, the detailed accounts of the 19 athletes in this study both provide support for a high level of EF processes in athletes *and* uniquely contributes to the EF literature due to its qualitative design. Further, these findings may lend support to the creation of more applicable EF assessments in future sport research in addition to offering accessible, athlete-generated language to describe different executive processes in sport that can be used to better explain EF to athletes, coaches and other sports staff.

Engaging in pre-play/game planning, organization and decision making

To the extent of our knowledge, no published research has investigated elite athletes' planning, except for in the context of career planning (Demulier et al., 2013). Although there has been little research solely on athletes' planning skills, related research on planning and goal setting in sports has received more attention. Locke and Latham (1985) propose that goals impact sport performance by engaging an athlete's effort and determination, by guiding their focus, and by encouraging strategy development (e.g., a plan). Therefore, superior goal setting in athletes may be due to their increased planning. This aligns with both Ercis (2018) and Sotoodeh and colleagues (2012) who determined that elite athletes reported significantly more game planning, and goal setting than non-elite athletes. The athletes in our study demonstrate their superior planning and organization skills as they prepare for games, starting as early as the week before. They then also use these executive processes during the game to make quicker decisions and maintain their team's defensive or offensive structure. According to Lezak (2004), successful planners must determine their options, weigh them and ultimately make choices necessary to promote the successful follow-through of their plan. Effective planning also requires impulse control, memory and sustained attention. Further, while research has shown that acute exercise leads to better planning in college students potentially due to exercise-induced physiological and biological fluctuations (Hung et al., 2013), there has been little research investigating the potentially reciprocal relationship with strong planning skills benefitting an athlete in their sport. According to the athletes, starting the game with their pre-game preparations and a game plan was crucial for success. Both the pre-game preparations and creation of a game plan before entering a game involve a high level of planning that was vital for the athletes and indicates the executive processes that occur even before actively involved in the game.

Similar to planning, little research has previously investigated organizational skills in athletes. Organizational skills in sport are the physical arrangement of one's environment and resources to best enable one's performance. Organizational skills, though, tend to be studied in early development, and there is a lack of current research investigating organizational skills in athletes. The athletes in our study described organizing both pre-game preparations as well as plays and their structure throughout the game. Being a student-athlete requires a high level of organization to maintain all their commitments effectively which was also reflected in athletes' descriptions. Having superior organizational skills was determined to be an asset in pre-game and pre-play cognitive processing that allowed the athletes to be more effective and better prepared throughout the game.

One of the essential EF processes the athletes discussed in their pre-play cognitive processing was decision making. Elite athletes tend to exhibit superior decision-making in their sport (Laborde & Raab, 2013; Raab & Johnson, 2007) and non-sport-related decisions (Gabbet et al., 2008) compared to nonathletes. Further, athletic expertise has been positively related to decision quality and negatively related to deliberation time (Vaughan, Laborde, & McConville, 2019). These superior decision-making skills may be due to the utilization of heuristic-driven decision-making strategies to quickly and simply deal with the complex situations within their sport (Hepler & Felts, 2012; Raab, 2012). Therefore, it is not surprising that our sample of athletes discussed their process of quickly making decisions in the game and how it depends on factors including the score, their team, the other team, and previous decisions.

Understanding athletes' use of planning, organization and decision making in pre-play and pre-game is important for sports psychologists, coaches and athletes in the future as they can focus on developing and perfecting these skills for future success.

Engaging in mid-play problem solving and purposive action

The quickest, most efficient EF processes need to occur when athletes have the ball and are actively involved in a play. We identified two EFs, problem-solving and purposive action, that were most often engaged when athletes had the ball. While occurring in less than a few seconds, problem-solving was described as having multiple steps aligned with Zelazo et al.'s (1997) problem-solving framework, including problem representation, planning, execution, and evaluation. William unknowingly discussed these steps when solving a problem: "First, identify the problem… (problem representation) stabilize the problem…if they're coming at you full speed… (planning), try and slow them in their tracks, delay their attack (execution)… and then, resolution…" (evaluation). Further, the athletes discussed having a hierarchy of options that they can cycle through, usually predetermined in the planning phase before they even have the ball. The option they will ultimately decide on to solve the problem is dependent on identifying the highest risk to reward ratio at the moment. Therefore, while athletes may initially intend to engage in an already planned and decided course of action, team sports are dynamic. The contingencies are constantly changing, so they may need to problem solve and develop a new solution or course of action mid-play.

In addition to problem-solving mid-play, the athletes engaged in the EF, purposive action. Purposive action is often discussed in terms of EF deficits or dysfunction (Lezak et al., 2004). Patients cannot perform the actions needed to follow through with their intention successfully (e.g., stating they want to visit a friend but never actually going). However, in the sporting context, we determined that Lezak et al.'s (2004) purposive action was the best depiction of an EF that captures athletes' descriptions of their thought processes when they have the ball. They intend (usually planned in pre-play moments) to shoot the ball and follow through with that intention by switching movements, updating their plan, and inhibiting irrelevant stimuli to follow through with their intention to shoot the ball. Purposive action could also be considered the united outcome of Miyake et al.'s (2000) three-factor model with inhibition, updating and shifting integrated into real life with actual actions and consequences. Therefore, engaging in purposive action is vital for the athletes to follow through with their intention and engage lower-order processes such as shifting, inhibiting, and updating.

Considering that when athletes are actively engaged in the play, they are constantly problem solving, and engaging in rapid cognitive processes known as purposive action, sports psychologists and coaches should focus on developing strong problem-solving skills in their athletes as well as focusing on the ability to quickly switch, inhibit and update their actions and thoughts (e.g., purposive action). This may help the athletes during the game as they are trying to quickly problem solve and follow through with their pre-determined intentions.

Engaging in post-play/game information processing, emotional control and effective performance

Externally paced athletes engaged primarily in three EFs, information processing, emotional control and effective performance following a play or at the end of the game. High levels of information processing were not unexpected, considering externally paced athletes are constantly obtaining new information from their environment due to the nature of their dynamic and unpredictable team sport. Elite athletes tend to perform better on tasks assessing information processing compared to their nonathlete counterparts (Chaddock et al., 2012; Rossi et al., 1992). Additionally, athletes tend to process information faster than nonathletes (Voss et al., 2010), perhaps due to their experiences requiring quick processing speed throughout the game to accomplish their desired course of action. Therefore, the athletes engaged in information processing often throughout the game following a play in which they needed to understand what just happened to prepare them for what is coming next.

Previous researchers have investigated emotional control and self-regulation strategies in athletes. There are many strategies that the athletes discussed to have successful regulation and control of their emotions which allows them to better focus on their performance. These strategies the athletes discussed (e.g., "have a check-in with yourself… One to ten, how am I feeling") align with the findings from quantitative research. For example, self-talk, imagery and activation in both practices and games were positively associated with regulating emotions in male collegiate athletes (Lane et al., 2009). Similarly, emotional control was significantly and positively related to mental toughness in both games and practice in male and female elite athletes (Crust & Azadi, 2010). Therefore, it seems emotional control is an essential EF process that occurs when a specific play or the entire game did not go as planned.

Effective performance was another EF athletes discussed engaging in moments after a play. Effective performance is the observation and following of one's performance and involves self-monitoring and self-regulation. It requires athletes to extract insightful information from their previous performance to increase their performance in the future. Thus, the athletes primarily discussed effective performance immediately after a play or game when they had more time and freedom to engage in this cognitive process. Previous research has found that self-monitoring (a component of effective performance) is associated with increased motor learning (Zimmerman & Kitsantas, 1996; Schempp et al., 2007), and athletes tend to have strong self-monitoring skills (Zimmerman & Kitsantas, 1996). Self-monitoring leads athletes to be more aware of errors, solve problems, and take corrective action (Tan, 1997; Berliner, 1986). In fact, self-monitoring can be considered vital to elite athletes' success; dozens of self-monitoring training programs have been conducted (Young et al., 2009; Polaha et al., 2004; Bell & Patterson, 1978; Kirschenbaum et al., 1982). Like emotional control, it was important for athletes to engage in the EF, effective performance, to better their performance in the future.

The three EFs engaged after a play or game, information processing, emotional control and effective performance, are vital to an athlete reflecting and succeeding in the future. It is important for both coaches and sports psychologists to be aware of these cognitive processes that athletes are engaging in so they can continue to develop and nurture these functions, similar to the research investigating the effects of self-monitoring on performance; developing information processing, emotional control and effective performance skills could lead to increased performance by the athletes as they learn from their mistakes and do not let their emotions take over.

Limitations

While this study helped further understand EF in sport from those directly involved, it is not without limitations. Due to the nature of qualitative research and the interview format, we may have missed out on important insights through the specific questions asked. This study could potentially be conducted using other qualitative approaches, including focus groups or surveys. However, interviews allowed us to gain the most information from athletes and allowed for a more dynamic and perceptive experience than other qualitative methods. It is also possible that an online format may have made it more difficult for participants to engage. However, considering video conferencing was used for classes this year due to COVID-19, the student-athlete participants were familiar and comfortable on video and were all incredibly involved throughout the interview. Lastly, our sample was primarily white, which may limit the experiences and ideas discussed.

Future Directions

Future research should expand on our findings and conduct more qualitative interviews with a broader range of athletes across different sports, genders, ethnicities, and ages. As previously stated as a limitation of this research, the sample consisted of primarily cisgender white participants; future studies should recruit more inclusive samples to better understand the experiences in sport for those from diverse backgrounds. Further, there may be differences in sport tactics and thinking across cultures other than primarily white Western cultures worth examining. It would also be interesting to conduct interviews with coaches or athletes from self-paced sports to gain their unique perspective and insight into EF in sport. Finally, utilizing a mixed-method approach in which athletes discuss the EF processes used during play and then are assessed for EF performance could provide valuable insight into the processes that athletes describe using compared to their objective level of executive functioning.

Conclusions

This qualitative study is the first to explore elite Canadian athletes' executive functioning from four different EP sports. While EF in sport has been of interest to researchers for many years, the focus has remained on investigating differences in EF performance between differing sports and levels of competition (e.g., elite athlete versus intramural athlete versus nonathlete). Until now, it has been unclear from an athletes' perspective how playing a collegiate sport may involve their EF. So, the qualitative interviews provided nuance to our understanding of EF in sport by gaining insight into what athletes are thinking when they are playing that neither tasks nor questionnaires can offer. We learned that depending on the timing and involvement in the play, athletes engage in different EFs such as planning and decision making in pre-play moments. Mid-game, the athletes engage their problem-solving skills and purposive action. They tend to self-monitor and process information after the play is complete. In conclusion, we have identified eight higher-order EFs (i.e., planning, organization, decision making, problem-solving, purposive action, information processing, emotional control, and effective performance) that are employed by athletes throughout different moments of the game. These findings ultimately provide an exciting contribution to the EF field due to its nuance and descriptions from the experiences of 19 elite Canadian university athletes.

Tables

Table 5. *Demographic information for all participants.*

Athlete	Age	Sport	Years of sport played	Months since last concussion	Number of lifetime concussions
Elijah	19	Soccer	14	15	3
Mia	21	Soccer	16	18	4
William	21	Soccer	18	11	2
Sasha	22	Soccer	18	26	2
Andrew	22	Soccer	15	2	5
Liam	22	Soccer	18	5	3
Sam	22	Soccer	19	20	4
Nathan	23	Soccer	19	14	2
Sophia	18	Rugby	5	15	1
Olivia	19	Rugby	5	22	5
Emma	19	Rugby	4	21	5
Henry	20	Rugby	7	12	4
Julian	21	Rugby	5	23	8
James	22	Rugby	12	11	6
Abby	24	Volleyball	13	34	2
Chris	25	Volleyball	10	10	4
Cameron	25	Volleyball	14	6	2
Kylie	23	Basketball	18	40	4
Colton	25	Basketball	21	24	4

Note. Pseudonyms have been used to protect participants' identities.

Table 6. *Interview Guide.*

1. Breaking the ice
    a. Tell me about your everyday life as a university athlete?
2. Strategic Planning
    a. Explain to me how you became a university athlete and what steps you took to get there?
    b. How do you prepare for a game?
        i. Prompt or cue: How do you mentally prepare?
    c. When you're playing, how do you stay focused on the game?
3. Decision making
    a. Tell me about how you determine what play to make during a game?
        i. Prompt/Cue: What is your thought process when making decisions?
        ii. Prompt/Cue: What are you thinking when deciding what to do?
    b. Can you think of a moment when the play you initially wanted to make didn't work out, how do you decide what to do next?
4. Problem-solving
    a. Can you think of an experience where you or had to solve a problem in a game?
5. Working memory
    a. In high-level sports, there can be a lot happening in your head at once. Can you explain to me what you are thinking about while playing?
    b. How do you process all the information running through your head during a game?
    c. How do you decide what thoughts to focus on?
6. Self-regulation
    a. Sports can sometimes be frustrating or upsetting. Can you think of a time when you had to control your thoughts or emotions?
7. Learning & growth
    a. Tell me about your process of learning and developing new skills in your sport?
    b. What are your thoughts on when learning new skills? What are you focused on mentally?
8. Overall:
    a. Do you have any other thoughts or comments to add about your thinking when playing?

Figures

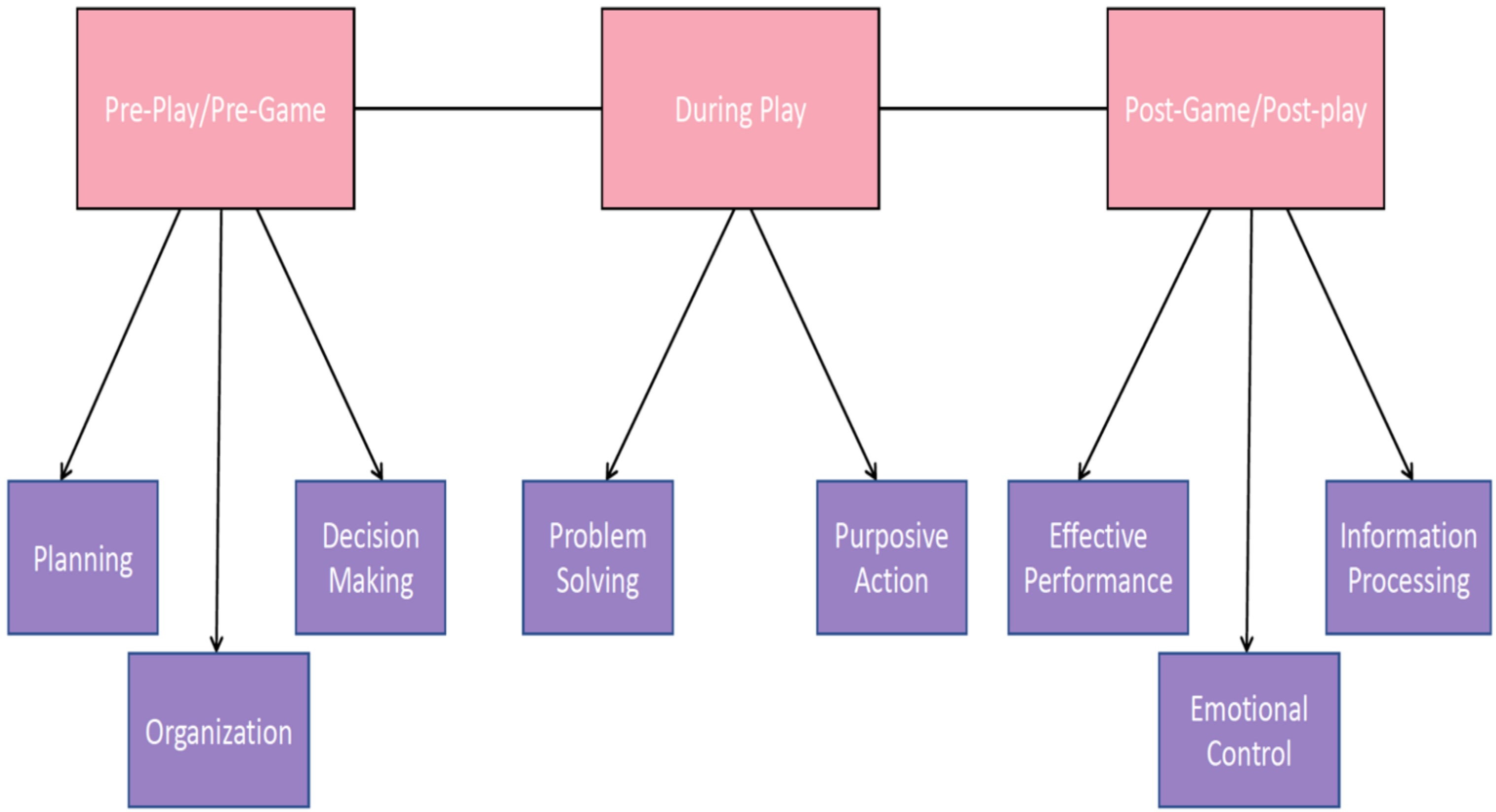

Figure 5. Thematic Map of Results.

Chapter 4: Conclusions

Considering that executive processes are engaged in a dynamic, novel, cognitively demanding environment, it is no surprise that researchers have been intrigued, for many years, by the relationship between executive function (EF) and physical activity, especially sports. Previous research has determined there is a positive relationship between EF and physical activity/sport through differing quantitative methods (Chueh et al., 2017; Daly et al., 2017; Jacobson & Matthaeus, 2014). However, previous research investigating this relationship has utilized differing methodologies and approaches to assessing EF, which leads to questions of the certainty of the supposed relationship between EF and physical activity/sport. For example, a study may use only one computerized inhibition task while another study may use a self-report measure, yet another may use a problem-solving task, and all would report assessing EF. Thus, the aim of my Master's thesis was to explore this relationship between EF and physical activity/sport using two different methodological approaches: 1) A robust quantitative assessment of EF with multiple computerized tasks for each EF process and a subjective self-report measure, and 2) A unique qualitative approach to better understand the executive processes used in sport. The findings of these independent yet complementary studies culminated in a better understanding of EF and its relationship with physical activity and sport.

The quantitative study first investigated the relationship between physical activity, athletic status, concussion history and EF. While I found a strong association between subjective EF and the predictors, physical activity, athletic status and concussion history, we found no relationship between those predictors and our objective measures of EF.

Secondly, the qualitative study aimed to understand the role of EF in elite externally paced sports athletes' experiences of the game, and we generated three themes to this end. The themes were: 1) Engaging in pre-play or pre-game planning, organization and decision making, 2) Engaging in mid-play problem solving and purposive action and 3) Engaging in post-play or post-game information processing, emotional control and effective performance. When examined together, the quantitative findings support the beneficial impact of physical activity and sport on the behavioural manifestations of EF that are engaged in everyday life and the qualitative findings provide nuance and detail to the specific behavioural EFs that may be most benefitted from sport participation.

Even though the strategic planning, organization and impulse control subscales were not significant in the quantitative regressions, the EFI total score was significant and may reflect associations between physical activity, sport and behavioural EF processes that the individual subscales could not. The qualitative study identified specific EF processes such as planning, organization, and impulse/emotional control that are engaged in sport. These processes are also reflected in the EFI questionnaire, which was significantly related to physical activity and sport (e.g., athletic status). The results of my thesis suggest that physical activity and sport may be more beneficial for real-life EF processes such as planning, organization and emotional control, rather than the latent factors often researched in quantitative research such as inhibition and shifting that isolated as they are in research have little real-life applications.

First, planning may be a critical executive process for athletes and those who are physically active. According to Lezak et al. (2004), efficacious planning involves determining and weighing one's options to make the required choice to execute the intended plan. The athletes in the qualitative study described starting the game with their pre-game preparations and how beginning a game with a plan was essential. Previous research has shown that acute exercise leads to better planning in college students, potentially due to exercise-induced physiological and biological fluctuations (Hung et al., 2013). While the strategic planning subscale was not significantly associated with physical activity and athletic status in our quantitative study, this may be due to our sample who most likely have strong strategic planning skills as university students leading to less variability. Further, this subscale is constrained to a few items that are general and apply to any context (e.g., academics, relationships, sport) which may lead to less nuance and description unlike our findings from the qualitative study that was focused in a sports context. Therefore, it would be interesting to investigate this further in athletes and those who are very physically active specifically, as it seems that planning may be an important executive process that is impacted by physical activity and sport and the preparation that both require to be successful.

Second, organization is another important EF related to sport and physical activity. Organization in sport can be described as the physical arrangement of one's environment and resources to enable one's performance best. According to the athletes in the qualitative study, pre-game organization, organizing plays, and positioning throughout the game, were a crucial part of their cognitive processing. Further, excellent organization was an asset throughout the game, causing the athletes to be more effective and better prepared. Similar to the planning subscale, neither physical activity nor athletic status was associated with the organization subscale in our quantitative study. The subscale focuses on organization broadly [e.g., I have trouble summing up information in order to make a decision with it” (reverse scored)] which differs from our qualitative study that provided more elaboration and nuance on organization used in sport, specifically. Therefore, while there may have been no unique effects of sport or physical activity on general organization skills, sport participation may play a role in the development of this executive process when in a specific sporting context. Researchers have yet to investigate the effects of physical activity and sport specifically on the executive process of organization and should be an area of future research to better elucidate this relationship.

Third, emotional control was identified by athletes as important to their success in a game and may also be relevant to physical activity and sport more broadly. The athletes discussed multiple strategies to control their emotions, such as checking in with themselves and taking deep breaths. Previous research has shown that self-talk, imagery and activation in both practices and games were positively associated with regulating emotions in male collegiate athletes (Lane et al., 2009). Similarly, emotional control was positively associated with mental toughness in male and female elite athletes (Crust & Azadi, 2010). In terms of physical activity more broadly, Pears and Sutton (2021) conducted a systemic review and meta-analysis on the effectiveness of Acceptance and Commitment Therapy (ACT) interventions for promoting physical activity and found small-to-medium effects. ACT uses acceptance-based approaches towards negative emotions without trying to eliminate or change them which may be partly related to fostering emotional control. Further, a recent narrative review discusses the importance of positive affect both related to physical activity and incidentally in the promotion of continued physical activity (Stevens et al., 2020). Thus, limiting of negative emotions before, during and after exercise may be crucial to future physical activity engagement. Also, in our quantitative study, the EFI has items regarding impulse control more broadly, which may relate to emotional control as one of the items is “I lose my temper when I get upset” (reverse-scored). Even though the specific impulse control subscale was not significant, this may be due to the range of items with some less relevant to emotional control (e.g., I make inappropriate sexual advances or flirtatious comments”). Thus, physical activity and sport participation seem to be beneficial to emotional control, specifically. Emotional control is an essential EF process that athletes engage in after making a mistake or when something does not go as planned. Participating in sport and physical activity may be predictive of emotional control, considering it is a process they mist continuously engage in to be successful.

In conclusion, more complex, behavioural executive processes are more challenging to assess and measure (e.g., how does one assess solely the executive process of purposive action with an objective computerized task?) but may be better predicted by and relate to life factors such as physical activity and sport participation. The results of my thesis provide support for future research to utilize and develop more unique and ecologically valid methods of measuring EF in the field of physical activity and sport.

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Appendix

Appendix A: Demographic Questions

Please answer the following questions about yourself.

What sex were you assigned at birth, meaning on your original birth certificate?

Female __
Male___

Which best describes your current gender identity?

Male ___
Female ___
Indigenous Two-Spirit ___
Something Else (such as gender fluid or non-binary) ___

I identify my ethnicity as (select all that apply):

Asian
Black/African
Caucasian
Hispanic/Latinx
Indigenous/Native American
Pacific Islander
Prefer not to answer
Something Else

How old are you?

Please Select... 18 19 20 21 22 23 24 25

What year of university are you in? _____________

What is your major or program of study? _______________
What is your current average grade point average (GPA) as expressed by a percentage? (sliding scale)

F 50 **A+**

Do you play any sports (e.g., varsity, intramurals, community leagues, leisure time, etc.)? Check all that apply.

Baseball
Basketball
Biking
Golf
Hockey
Lacrosse

Rowing
Rugby
Running
Skiing/Snowboarding
Soccer
Swimming
Tennis
Volleyball
Yoga
I don't play any sports
Other (please specify)

What sport did/do you play at the highest level? _______________

What is the highest level that you have played at? _______________

What is your success at this level? (e.g. provincial or national championships, MVP, etc.) _______________

How many years have you played at this highest level?

N/A
Less than two years
2 - 5 years
5 - 8 years
More than 8 years

Have you ever experienced...?

3 or more concussions __________
2 concussions __________
1 concussion ___________
No history of concussions _____________

If you have experienced one or more concussions, when was the most recent? ____

Appendix B: Executive Function Index

	Rate how well each of the following statements describes you.	Not at all		Somewhat		Very much
1	I have a lot of enthusiasm to do things.	1	2	3	4	5
2	When doing several things in a row, I mix up the sequence	1	2	3	4	5
3	I try to plan for the future	1	2	3	4	5
4	I can sit and do nothing for hours.	1	2	3	4	5
5	I take risks, sometimes for fun.	1	2	3	4	5
6	I have trouble when doing two things at once, multi-tasking	1	2	3	4	5
7	I'm interested in doing new things.	1	2	3	4	5
8	I have a lot of concern for the well being of other people.	1	2	3	4	5
9	I'm an organized person.	1	2	3	4	5
10	I save money on a regular basis.	1	2	3	4	5
11	I do or say things that others find embarrassing.	1	2	3	4	5
12	People who are foolish enough to be taken advantage of deserve it.	1	2	3	4	5
13	I only have to make a mistake once in order to learn from it.	1	2	3	4	5
14	I tend to be an energetic person.	1	2	3	4	5
15	I make inappropriate sexual advances or flirtatious comments.	1	2	3	4	5
16	When someone is in trouble, I feel the need to help them.	1	2	3	4	5
17	I sometimes I lose track of what I'm doing.	1	2	3	4	5
18	I feel protective towards a friend who is being treated badly.	1	2	3	4	5
19	I think about the consequences of an action before I do it.	1	2	3	4	5
20	I lose my temper when I get upset.	1	2	3	4	5
21	I take other people's feelings into account when I do something.	1	2	3	4	5
22	I have trouble summing up information in order to make a decision with it.	1	2	3	4	5
23	I start things, but then lose interest and do something else.	1	2	3	4	5
24	I swear/use obscenities.	1	2	3	4	5
25	I don’t like it if my actions or words hurt someone else	1	2	3	4	5
26	I use strategies to remember things.	1	2	3	4	5
27	I monitor myself so that I can catch any mistakes.	1	2	3	4	5

Appendix C: Godin-Shephard Leisure Time Activity Questionnaire

Godin Leisure-Time Exercise Questionnaire

INSTRUCTIONS

In this excerpt from the Godin Leisure-Time Exercise Questionnaire, the individual is asked to complete a self-explanatory, brief four-item query of usual leisure-time exercise habits.

CALCULATIONS

For the first question, weekly frequencies of strenuous, moderate, and light activities are multiplied by nine, five, and three, respectively. Total weekly leisure activity is calculated in arbitrary units by summing the products of the separate components, as shown in the following formula:

Weekly leisure activity score = (9 × Strenuous) + (5 × Moderate) + (3 × Light)

The second question is used to calculate the frequency of weekly leisure-time activities pursued "long enough to work up a sweat" (see questionnaire).

EXAMPLE

Strenuous = 3 times/wk

Moderate = 6 times/wk

Light = 14 times/wk

Total leisure activity score = (9 × 3) + (5 × 6) + (3 × 14) = 27 + 30 + 42 = 99

Godin Leisure-Time Exercise Questionnaire

1. During a typical **7-Day period** (a week), how many times on the average do you do the following kinds of exercise for **more than 15 minutes** during your free time (write on each line the appropriate number).

Times Per Week

a) STRENUOUS EXERCISE
(HEART BEATS RAPIDLY)
(e.g., running, jogging, hockey, football, soccer, squash, basketball, cross country skiing, judo, roller skating, vigorous swimming, vigorous long distance bicycling) __________

MODERATE EXERCISE

(NOT EXHAUSTING) ____________
(e.g., fast walking, baseball, tennis, easy bicycling, volleyball, badminton, easy swimming, alpine skiing, popular and folk dancing)

b) **MILD EXERCISE**
(MINIMAL EFFORT) ____________
(e.g., yoga, archery, fishing from river bank, bowling, horseshoes, golf, snow-mobiling, easy walking)

2. During a typical **7-Day period** (a week), in your leisure time, how often do you engage in any regular activity **long enough to work up a sweat** (heart beats rapidly)?

OFTEN	SOMETIMES	NEVER/RARELY
1. |_|	2. |_|	3. |_|