# The Effect of Dual-Tasking on Information Processing in Contact Sport Athletes: Examining the Long-term Effects of Self-reported Concussion

by

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## Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

**Anthony Tapper**

**Abstract**

Objective: Concussions have been linked to deficits in executive functions including, memory and attention, and oculomotor dysfunction, all of which are required to play safely and successfully at an elite level. The goal of the current research was to understand the information processing abilities of varsity hockey athletes in attempts to determine the long-term effects of concussions. Additionally, our research compared clinical and experimental neurocognitive tests for discriminating athletes with and without a history of concussion who have returned-to-play. Since hockey players need excellent memory, attention, and executive function skills, a novel dual-task paradigm was developed by incorporating tasks that require visuospatial working memory and auditory processing.

Method: Participants were 29 varsity collegiate ice hockey players (15 females, mean age= 19.1 ±1.26, 14 males, mean age= 22.7 ± 1.3). Eighteen athletes were diagnosed with a history of concussion based on self-report questionnaires, health history questionnaires, and prior physician diagnosis. The number of concussions were reported as follows: one (n = 9), two (n = 7), and three (n = 2). Participants performed a dual-task involving visuospatial working memory (Corsi block test) and auditory tone discrimination. Each task was presented individually (Vis-Single, Aud-Single), then simultaneously (VisAud-Dual). Eye movements were recorded using the Eyelink II eyetracker during the experimental tests. Also, participants completed a clinical neurocognitive test for concussions called the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT). The main outcome measures were the Corsi block memory span and auditory tone discrimination accuracy. Four ImPACT composite outcome variables were measured including, Verbal Memory, Visual Memory, Visuomotor Processing Speed, and Reaction Time. Finally, the four oculomotor outcome variables measured were rate of task-relevant saccades, microsaccades, and other saccades, and saccade gain. Statistical analyses were completed using 2 and 3-way mixed ANOVA's, and logistic regressions. The independent factors were two within-subject variables, Task Condition (single, dual), and Difficulty Level (# of targets to remember ranging from 3 to 7) and the between-subject variable was Concussion History (concussion, no concussion).

Results: A 2-way mixed ANOVA on tone discrimination accuracy showed athletes with a history of concussion performed significantly worse on the tone discrimination task in the dual-task condition compared to the non-concussion athletes. No significant differences were shown when each task was performed alone, or on the Corsi block test in the dual-task condition. Two separate logistic regression models using ImPACT composites and dual-task measures identified auditory cost as the only significant predictor for Concussion History. Additionally, the dual-task test was more sensitive for discriminating athletes with and without a history of concussion compared to the ImPACT. A 3-way mixed model ANOVA on task-relevant saccades, microsaccades, and other saccades showed no significant differences between athletes with and without a history of concussion. However, a medium effect size was found for task-relevant saccades, which showed that athletes with a history of concussion had a higher rate of saccades. Additional analysis examining saccade gain for both horizontal and vertical saccades showed no significant difference between concussion history groups; however, a medium effect size was found which showed that athletes with a history of concussion had a higher saccade gain.

Conclusions: Athletes with a history of concussion may have persistent deficits in executive functions. These deficits were only evident in previously concussed athletes when cognitive resources were stressed during the dual-task condition. In comparison to current clinical neurocognitive tests

designed for concussions (i.e., ImPACT), tests examining executive functions appear to be more sensitive for discriminating athletes with and without a history of concussion, thus, should be included in current evaluation protocols. Finally, there were no statistically significant differences in gaze strategies; however, with the addition of more participants, gaze strategies may provide useful information into how athletes with and without a history of concussion encode visuospatial information. Therefore, further evaluation into encoding strategies may be helpful for developing training protocols for a safe return-to-play.

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## Section 1: General Introduction

### 1.1 Significance of Concussions

Concussions are an ongoing topic in sports and recreation. There is an estimated 1.6 to 3.8 million sports related concussions annually, with the majority of them being concussions (Daneshvar, Nowinski, McKee & Cantu, 2011). Concussions occur from direct or indirect biomechanical forces to the head inducing a complex pathophysiological process affecting the brain (Clay, 2013). A variety of signs and symptoms can be present after a head impact, including balance or memory loss, slowing of saccadic eye movements and problems dividing attention (Register-Mihalk, Littleton & Guskiewicz, 2013; Dziemianowicz, 2012; Berstein, 2002). Recent research (Dziemianowicz, 2012; Clay, 2013) has demonstrated a series of long-term functional impairments after multiple or severe concussions, including post-concussion syndrome (PCS), increased odds for dementia, and emotional disturbances such as depression. The increasing frequency of sport-related concussions has placed a serious concern in the sports community as athletes continue to be placed in an environment risking further injury. Consequently, early return to play without proper recovery places athletes at risk for catastrophic consequences, such as second-impact syndrome or possible death (Boden, 2013). Therefore, understanding the long-term effects of concussions will assist with the proper management of head injuries to allow athletes to return to play safely.

### 1.2 Current Tests

Our current scientific knowledge on the accuracy to track concussion recovery is limited, thus, many athletes disobey concussion protocols (Dziemianowicz, 2012). Currently, there are several concussion management tools used in professional and amateur sports, such as the

Immediate Post-Concussion Assessment and Cognitive Test (ImPACT), the Sport Concussion Assessment Tool (SCAT), the King-Devick test, the Balance Error Scoring System (BESS) and the Standard Assessment of Concussion (SAC), yet, there is no single test that has the ability to accurately track an athlete's recovery following a concussion. For example, the ImPACT has been shown to predict as much as 80% of individuals with a diagnosed concussion (Dziemianowicz, 2012; Broglio, Macciocchi & Ferrara, 2007; Schatz et al., 2006) but scores are typically back to baseline within 5-10 days. Although the ImPACT is relatively successful at diagnosing concussions, the ability to track recovery and identify persisting deficits has not seen as much promise as most participants with a history concussion in the chronic phase show no deficits on the ImPACT's cognitive measures (Broglio, Ferrara, Piland, & Anderson, 2006; Maerlender et al., 2010; Iverson, Brooks, Lovell, & Collins, 2006; Van Kampen et al., 2006). This error in the accuracy to track recovery can lead to athletes returning to play unsafely and risking further injury. Thus, without proper recovery athletes can have persisiting problems that can affect athletic performance. One possible explanation for this detection error surrounds the complexity of the neuropsychological tests included in the ImPACT, as this test may not place enough load on cognitive processes.

The Sport Concussion Assessment Tool (SCAT) and the King-Devick tests are two other well recognized tests used for diagnosing concussions, yet little research has been done to measure its effectiveness at tracking recovery. For instance, the SCAT does not have a scoring system to accurately diagnose a concussion (McCrory et al., 2009) whereas the King-Devick test is a relatively new test that provides a limited data set for concussion tracking (Dziemianowicz, 2012). A common limitation amongst these tests is their inability to represent contact sport athletes that compete in a variety of dynamic sporting environment (Register-Mihalk, Littleton &

Guskiewicz, 2013) which commonly involves processing multiple sensory inputs simultaneously. Since elite team sport athletes differ in their cognitive abilities compared to novice athletes (Mann et al., 2007), it is important to consider these skills when developing a test that is sensitive to the long-term effects of concussions.

**1.3 Studying Athletes**

Figure 1.1

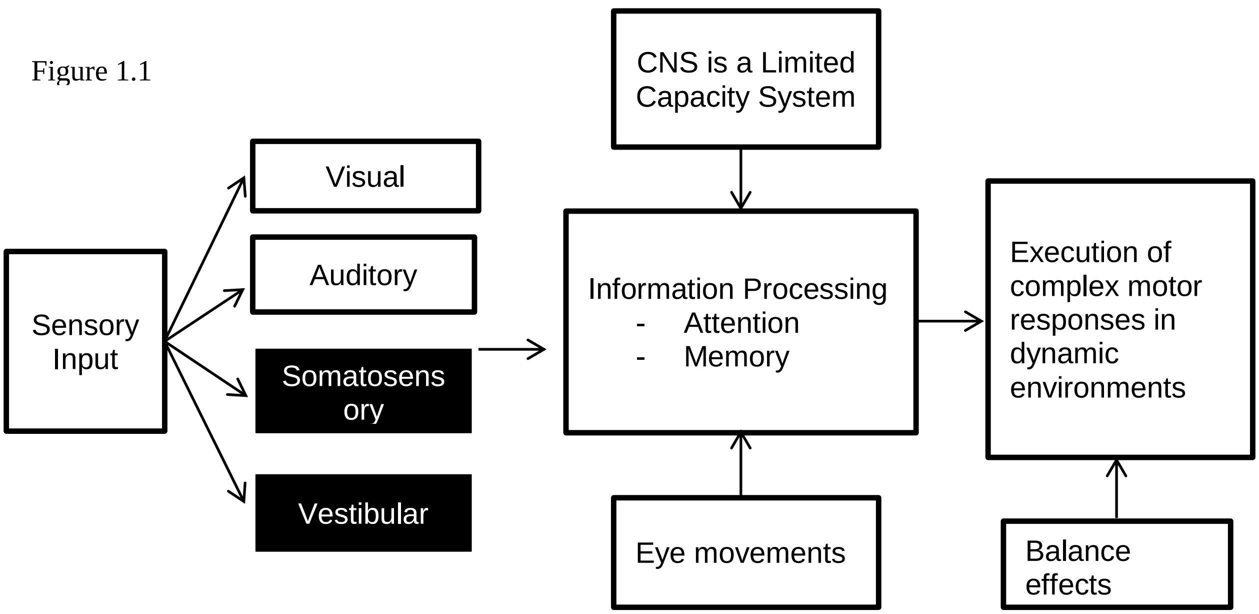


**Figure 1.1**: An information processing framework for elite team sport athletes.

Athletes, specifically elite team sport athletes, possess a variety of sport-specific cognitive abilities (i.e. visual search behaviours, anticipation, focused attention, sport specific memory) compared to novice athletes (Williams, 2000; Mann et al., 2007; Voss et al., 2010). These cognitive abilities improve an athlete’s ability to process complex and rapidly changing environments (Voss et al., 2010). It is these cognitive abilities that separate experts from non-experts and allow experts to compete safely and effectively.

In the neuropsychological literature (Voss et al., 2010; Mann et al., 2007), sports that involve simultaneously processing an extensive amount of information including teammates, opposing players, referees, and objects (i.e. puck or ball) are often referred to as 'strategic' sports. In strategic sports, elite athletes must use multiple sensory inputs to develop an accurate view of their dynamic environment so they can execute complex motor responses for each situation. For example, ice hockey players must have the ability to integrate multiple sensory inputs (i.e. visual information from the environment and auditory information from other players) to execute a variety of game play motor skills (i.e. passing a puck while avoiding sticks, players and referees) under a restricted time and space. Therefore, the ability to complete complex motor responses is largely dependent on the acquisition of relevant information by using processing resources of attention and memory. After all, extracting relevant information from the environment allows athletes to complete a task successfully while avoiding obstacles that can cause injury.

To date, few research studies have addressed information processing demands in team sport athletes using a dual-task paradigm. Dual-tasking is a term used to describe the ability to accurately process information by dividing attentional resources between multiple tasks (Chan, Shum, Toulopoulou, & Chen, 2008; Friedman et al., 2008; Vallat-Azouvi, 2007). A dual-task paradigm helps researcher's gain an understanding of sport specific performance as it stresses information processing resources (i.e. attention and memory) that play a vital role in performance. Furthermore, dual-task paradigms resemble strategic sports because dual-tasking increases task difficulty by involving the simultaneous processing of different sensory inputs. Therefore, dual-tasking can be used as a possible research method to study strategic sport athletes that are constantly required to multi-task to perform successfully and avoid injury (Vestberg et al, 2012).

Studies examining the effects of dual-tasking in team sport athletes have been limited, but, three studies have examined the cognitive demand of sports like hockey and soccer (Leavitt, 1979; Smith & Chamberlin, 1992; Fait et al., 2011). Leavitt (1979) and Fait et al. (2011) completed a variety of dual-tasking studies on ice hockey players by adding secondary interference tasks (i.e. stick handling, visual Stroop task, obstacle avoidance) to a primary speed skating task. They found that novice players had significantly slowed their skating speed while completing secondary tasks of stick handling and visual interference. Meanwhile, elite players were able to maintain a fast skating speed while completing the secondary tasks (Leavitt, 1979). Fait and colleagues (2011) expanded on the paradigm by examining obstacle avoidance as an interference task. A total of eight competitive youth hockey players were studied using the same protocol as Leavitt (1979), except additional trials were added that included obstacle avoidance. The main goal of this experiment was to identify if adding obstacles affected movement time and cognitive performance. They found that obstacle avoidance took priority while dual-tasking as a higher number of errors occurred on the Stroop task in trials with an obstacle but no difference in skating speed was present. Fait and colleagues (2011) identified that obstacle avoidance does affect cognitive performance while dual-tasking; thus, stressing the importance of avoiding obstacles that can result in injury. This literature (Leavitt, 1979; Fait et al., 2011) provides evidence that elite hockey players have greater cognitive abilities to complete multiple sport specific tasks simultaneously with obstacle avoidance being a primary goal. Similar findings were found by Smith and Chamberlin (1992) when conducting an experiment on novice, intermediate and expert soccer players. Smith and Chamberlin (1992) found that experts were significantly better then intermediate and novice soccer players at running through a slalom course while dribbling a soccer ball. Therefore, the following studies (Leavitt, 1979; Smith & Chamberlin, 1992; Fait et al., 2011) show that expert athletes have greater cognitive abilities when performing multiple sport specific tasks concurrently.

Since most concussion tests do not study athletes in tasks related to their sport, it is important to see if an athlete's cognitive abilities are transferable to a lab setting. In a recent literature review by Voss and colleagues (2010), it was found that athletes outperformed non-athletes on numerous laboratory tasks requiring attention, memory, and processing speed. Voss and colleagues (2010) characterized these tasks as varied attention paradigms which included the Paced Auditory Serial Addition Task (PASAT), the Eriksen arrow flanker task, and tasks of visual short term memory and visual discrimination. Therefore, we must be cautious of these cognitive abilities when comparing athletes with previous history of concussion to healthy controls as injured elite players may still outperform other healthy athletes.

Elite athletes are often recognized as superior performers at sport related skills that require cognitive processes such as attention. Of the many cognitive processes (ex. attention, decision making, problem solving), attention and working memory have been found to play an important role in expert performers compared to non-experts (Faubert & Sidebottom, 2012; Mann et al., 2007; Williams, Davids & Williams, 1999). Attention allows athletes to ignore irrelevant sensory information (i.e. the fans cheering) while extracting relevant cues from the environment (i.e. puck and player position). Also, attention plays a vital role in an athlete's ability to execute complex motor responses such as stick handling while skating. Meanwhile, memory provides a structure for completing these tasks by storing the relevant information until it can be recalled to complete an action. For example, an ice hockey player must divide attention between visual and auditory stimuli and hold that information to create an understanding of where players are on the ice. Therefore, attention and memory are important information processing resources to elite athletes and need to be considered when developing a test to track concussion recovery.

## Section 2: literature Review

### 2.1 Defining Attention

Attention is the process of allotting information processing resources to complete a cognitively demanding task or understand a target of interest (Posner, 2012; Gersh et al., 2008). Moreover, attention allows humans to engage and sustain interest towards stimuli in their environment, and carry out complex tasks by effectively perceiving and processing the task at hand. In the literature, attention has been defined as a limited capacity system that includes orienting and detecting information while maintaining alertness (Petersen & Posner, 2012; Desimone & Duncan, 1995). The detecting system has been labelled under 'executive functioning' which allows for focusing attention on a task or a target (Peterson & Posner, 2012). In neuropsychology, the term 'executive function' has no consistent definition but is commonly used to describe the cognitive processes that allow humans to solve problems, set goals, and divide/switch attention between one or more concurrent tasks (Peterson & Posner, 2012; Friedman et al., 2008; Strauss et al., 2006). Furthermore, the executive function system is used to make select the relevant incoming sensory input and ignore irrelevant stimuli to generate an action that successfully completes a goal. Therefore, attention plays a vital role in every human's ability to complete daily tasks effectively.

Most of the research conducted on attention is concerned with studies in the context of vision, especially in the area of gaze tracking, as there has been strong evidence in the connection between attention and shifts in gaze (Posner, 1980; Hoffman & Subramaniam, 1995). For example, Hoffman and Subramaniam (1995) designed two experiments that examined the link between attention and shifts in gaze. Experiment one tested whether or not saccades were the result of a preceding shift in attention by having subjects fixate on a central cross and correctly recall letters which quickly appeared then disappeared in peripheral locations. They found that participants were able to correctly recall the letters before making eye movements to those locations, which indicates that a shift in visual attention comes before an eye movement to that location. In experiment two, participants were asked to attend to one location while making a saccade to the same location or another location. Hoffman and Subramaniam (1995) found that participants were able to detect targets better when the saccade was made to the same location opposed to a different destination. Additionally, a significant difference in errors recalling the target was present when the target was at the same location as the saccade. This research provides evidence that a link exists between attention and shifts in gaze; therefore, we can then infer that a shift in gaze includes a shift in attention. However, a shift in attention can occur without a saccade.

Attention shifts can occur through two different mechanisms; firstly, a gaze shift towards an object in order to bring the target onto the fovea is termed overt attention shift. Alternatively, a separation between gaze and attention can occur as environmental information in the periphery can be perceived and processed without a shift in gaze, this process is termed covert attention (Ball et al., 2013; Posner, 2012; Sperling, 1960; Munn & Geil, 1931). In the literature, it has been shown that a tight coupling exists between overt and covert attention (Posner, 2012; Hoffman & Subramaniam, 1995) as humans must covertly shift their attention before overtly making an eye movement. This was explained in the previous paragraph in the experiments conducted by Hoffman and Subramaniam (1995). These two attention shifting mechanisms are used to select environmental information but, storing targets into visuospatial working memory may rely more strongly on the use of one of the attention shifting mechanisms.

## 2.2 Defining Working Memory

Visuospatial Working Memory (VSWM) is a multi-component system that allows humans to comprehend their immediate environment and manipulate incoming information to complete a goal (Baddeley, 1992). This system allows humans to retain new information and solve problems by processing relevant stimuli from the environment (Baddeley, 1992). The term visuospatial working memory is commonly defined in the literature as the ability to recall and manipulate all visual information, as well as spatial information from other modalities (Ball, Pearson, & Smith, 2013). The term working memory stems off the concept of short term memory which refers to a single storage mechanism that holds information for a short period of time (~30 seconds) (Baddeley, 1992). In everyday tasks, visuospatial working memory provides the basis for understanding moment to moment interactions by providing humans with a mental representation of their environment. Thus, visuospatial working memory is an important concept that provides the substrate to interact with the environment effectively..

## 2.3 History of Working Memory

The concept of working memory has been attributed to George Miller (1956). Miller used the term "variance" to describe the amount of information humans can accurately process and recall. Although the term "working memory" as we know it today was not yet developed, Miller used the term "immediate memory" to characterize how humans collect, process, and recall immediate information (Miller, 1956). The terms "variance" and "immediate memory" are related as individuals only have the ability to process and recall a limited amount of information. Miller described how the amount of information processed was dependent on a human's ability to 'chunk' information together. In Miller's case, the term 'chunking' was used to explain the process of grouping familiar units together to create a sequence that can be tapped into for the immediate recall of information such as, targets or numbers (Miller, 1956). Miller's initial work was the basis of working memory knowledge and led to the transition of terminology from immediate memory to working memory (Miller, Gallanter & Pribram, 1960).

Subsequent studies on working memory were carried out by Atkinson and Shiffrin (1968). Atkinson and Shiffrin created a three component model consisting of the sensory register, short-term memory, and long-term memory. They believed that working memory was a secondary component to the sensory register that led to the storage information. In their model, the sensory register receives incoming sensory information and stores it for a brief amount of time (~500ms for vision, 3-4s for auditory) until it is lost or sent to short-term memory. For short-term 'working memory' to receive sensory information, attentional mechanisms are needed to focus on the information for further processing. As a result, short-term 'working memory' accepts specific inputs from the sensory register and pairs it with long term memory. The working memory component is needed to send rehearsed information to long term memory, but, if not rehearsed, will begin to diminish within 30 seconds of presentation (Atkinson & Shiffrin, 1968). Atkinson and Shiffrin confirmed a diminishing short term working memory when conducting experiments that had participants complete a number-letter pairing task. In this task, participants were shown a series of number-letter pairs (i.e. 31-K) starting with one pair and increasing in complexity to 17 pairs. They found that memory diminished when more pairs were added as the first number-letter pair could not be remembered when new pairings were shown. Atkinson and Shiffrin provided valuable information on the whole memory system as a possible timeline for holding items in short term memory was developed. Although this model gained insight into the role of working memory, it did not provide an in-depth examination on further components of working memory.

In 1974 Alan Baddeley and Graham Hitch expanded the knowledge of working memory by transitioning from a unitary store of working memory (Miller, Gallanter & Pribram, 1960; Atkinson & Shiffrin, 1968) to a multi-component model. For example, Baddeley suggested that multiple items could be stored simultaneously opposed to one at a time. Originally, Baddeley created a three component model on working memory that consisted of a central executive control system and two temporary storage slave systems called the phonological loop and visuospatial sketchpad. These temporary storage systems were further divided into two supplementary components consisting of passive and active processes. The phonological loop's supplementary components include a phonological store (passive) and rehearsal system (active). The visual spatial sketchpad consists of a visual cache (passive) and inner scribe rehearsal system (active) that allows for information to be passed into long-term memory. The central executive control system was thought to be the primary link to working memory as it managed the two slave systems by switching attentional mechanisms for the encoding and retrieval of material (Baddeley, 1992). The central executive also has the ability to manipulate the stored material within the two slave systems for goal processing purposes (Baddeley, 1992; Baddeley, 1996).

Over the past decade, a fourth 'episodic buffer' component was added to Baddeley's working memory model to account for the inconsistencies in research of the central executive control system (Baddeley, 2003). These inconsistencies were developed because there was a missing connection between long term memory and working memory. The episodic buffer was added to provide a link between long term memory and working memory, and act as a mechanism to model the environment for new cognitive representations (Baddeley, 2000). In the literature, it has been proposed that the episodic buffer acts as a storage area for the central executive and has the ability to combine information from the two slave systems and long term memory (Baddeley, 2003). For the purpose of our experiment, the visual spatial sketchpad and the central executive control system will be of main importance as the two tasks being used will tap into the spatial store of the visual spatial sketchpad.

### 2.4 Baddeley's Working Memory Model

The working memory model proposed by Baddeley and Hitch (1974) has been a popular framework for the temporary storage of information. The central executive control component is a limited capacity system that deals with information processing and cognitive functioning (McDowell, Whyte, D'esposito, 1997). The central executive deals with complex tasks by allocating attentional resources so that working memory can store multiple bits of information until it needs to be recalled. This system can hold approximately five items until a systematic decline begins and online information is lost (Luck & Vogel, 1997; Furley & Memmert, 2010). In a dual task paradigm, the central executive plays an important role in processing multiple tasks at once. Baddeley (1996) suggested that the ability to perform two tasks simultaneously is governed by the central executive as this mechanism produces a resource sharing effect between tasks.

Recent research (Vestberg et al., 2012; Register-Mihalk, Littleton & Guskiewicz, 2013) has shown that the central executive is an important system used to process one or more complex tasks. Vestberg and colleagues (2012) examined the central executive system using a design fluency test in which fifty-seven elite, novice, and normal athletes had to connect four dots in a square with one line. The goal of the task was to create as many combinations as possible in one minute without producing the same result twice. Therefore, the central executive is measured through many components, including working memory, response inhibition, and creativity. They found that the central executive system was significantly greater in elite athletes as they had more combinations than novice and normal athletes. Further research (Berstein, 2002; Howell, Osternig, Van Donkelaar, Mayr, & Chou, 2013; Martini et al., 2011; Register-Mihalik et al., 2013) on the central executive has shown that this system is affected by concussions. In the meta-analysis conducted by Register-Mihalik and colleagues (2013), it was shown that the central executive is significantly affected by concussions as participants with a concussion performed significantly worse on many complex dual-tasks. The dual-task paradigms included a primary gait task with a variety of secondary mentally demanding tasks (i.e. Stroop task & math questions). Although the central executive is important during dual tasks, we must also consider the visual spatial sketchpad component of Baddeleys working memory model.

The visual spatial sketchpad has the ability to temporarily store and manipulate visual and spatial information (Logie, 1995). This component is of specific importance as it can encompass visuospatial working memory (Logie, 1995). Visual spatial working memory is a form of information processing that refers to the ability to temporarily store and replicate visuospatial information (Logie, 1995). The visual cache is the passive component that is used to store the physical properties of an item such as its shape and colour (Logie, 1995; Beschin, 1997). The inner scribe handles the spatial and movement information of objects as it encodes the location or orientation of an object (Logie, 1995; Beschin, 1997).This component also has the ability to rehearse important information until it needs to be recalled. Furthermore, the visual cache and inner scribe work together to create a visual representation of environmental stimuli. A common neuropsychological test used to examine the visual spatial sketchpad and central executive is the Corsi Block Test.

### 2.5 The Corsi Block Test

The Corsi block test (Corsi, 1973) was developed in 1972 by Philip Corsi as a visuospatial counterpart to the verbal span test (Milner, 1971). It has gained much recognition over the years as it is commonly used to examine visuospatial short term memory in adults (Smyth & Scholey, 1992), athletes (Furley & Memmert, 2010) and participants with neuropsychological deficits after brain injury (Fork et al., 2005). The initial design included nine blocks (3x3x3cm) asymmetrically scattered on a wooden board. Over the years, the test has been translated onto computer monitors for the ease of administration and data collection. In the computerized version, all blocks are the same colour (i.e. blue) at the beginning of the trial then one block at a time changes colour (i.e. red) in a predetermined order. Participants are asked to recall the location of the blocks that changed colour in their order of presentation. The test increases in difficulty, commonly beginning with a sequence of two blocks and ending with a larger sequence (ex. eight blocks) when recall is no longer correct. Many studies (Smyth & Scholey, 1992; Furley & Memmert, 2010; Vandierendonck, Kemps, Fastame & Szmalc, 2004; Vecchi & Richardson, 2001) have used the Corsi block test to examine the working memory components from Baddeley's model.

The studies examining performance on the Corsi block test have shown that the working memory components of the task require support from the visuospatial sketchpad and central executive (Vandierendonck et al., 2004; Vecchi & Richardson, 2001). Vandierendonk and colleagues (2004) explored the visuospatial sketchpad's contribution to working memory by having participants complete five task conditions, including the Corsi block test on its own and four conditions pairing it with a secondary task. The four secondary tasks included articulatory suppression, matrix-tapping, random-interval generation, and fixed interval generation, which were used to tap into the visuospatial sketchpad and phonological loop. Vandierendonck and colleagues (2004) found that the Corsi block test requires support from the visual spatial sketchpad since performance was impaired when completing a secondary visuospatial task (i.e. Matrix-tapping) and not impaired during the articulatory suppression task that receives support from the phonological loop. They also reported that the central executive plays an important role in the Corsi block test when a sequence length extends beyond four items since memory load increases and requires extra resources to assist with the maintenance of visuospatial memory. Therefore, the central executive and visual spatial sketchpad play an important role to spatially locate and recall objects in an environment.

**2.6 Linking Attention and Working Memory**

In the literature, it has been shown that a link exists between attention and visuospatial working memory (Awh, Vogel, & Oh, 2006; Posner, 2012). There is strong evidence to demonstrate a connection between visuospatial working memory and attention (Theewes, Kramer & Irwin, 2011; Awh & Jonides, 2001) as the ability to recall a target is affected by attention (Gersh et al., 2008; Smyth & Scholey, 1994). For example, Awh, Jonides, & Reuter-Lorenz (1998) studied the overlap of attention and visual spatial working memory through the use of a choice reaction time (CRT) task with a spatial working memory task. In this task, the position of the stimulus from the choice reaction time task was either located in the same area of the spatial memory task or fell outside the area of the memory task. Awh and colleagues (1998) found that reaction times were faster when the choice reaction time stimulus was located in the same area as the memory task stimuli opposed to other areas. This evidence confirms an overlap of attention and working memory as stimuli that were previously held in working memory resulted in faster reaction times. This overlap has been consistent in recent research studies (Theewus, Belopolsky & Olivers, 2009; Theewus, Kramer & Irwin, 2011) that have captured the link between working memory and attention by using different visual working memory tasks. The ability to link these two cognitive processes has stemmed off studies (Hoffman & Subramaniam, 1995; Awh, Jonides & Reuter-Lorenz, 1998) that used gaze as a predictor of attention. Since attention can be inferred through gaze behaviours, and attention is strongly linked to visuospatial working memory, it is possible that gaze behaviours can predict success in a visuospatial working memory task.

Gaze behaviours are comprised of different components such as saccades, frequency of fixations, and fixation duration, which can affect performance on sport specific tasks like shooting a basketball (Mann, Williams, Ward & Janelle, 2007). Research has shown (Mann et al., 2007) that saccades, frequency of fixations, and fixation duration are important components of gaze behaviours that help athletes observe their environment. Saccades are eye movements that can be characterized as fast ballistic changes in eye position that occur approximately 3-4 times per second (Becker, 1991). Since voluntary saccades are shifts in gaze, these are representative of overt shifts in attention (Hoffman, 1998). Although saccades are helpful in rapidly moving between targets, they only allow for the processing of visual information when a pause occurs between successive saccades (Mann et al., 2007). A fixation occurs when the eye becomes stable due to a pause in saccade and can last between 150ms to 600ms (Hoffman, 1998;

Irwin, 1992). During this time of fixation, it is thought that visual information can be perceived and processed (Hoffman, 1998) with more information being extracted based on the length of fixation (Mann et al., 2007). It is important that saccades are made to the correct location to allow for environmental information to be processed in the high acuity fovea (Posner, 2012); however, information can also be extracted in the periphery using covert attention. While athletes are fixating on a target, peripheral vision is needed to determine the next fixation location or extract more information about the environment (Hoffman, 1998). Therefore, saccades, fixation duration, and frequency of fixations are important in an athlete's ability to extract relevant information to make a proper goal directed movements.

Studies on athletes have revealed that expert athletes possess excellent perceptual-cognitive skills, such as attention allocation, to extract task-relevant information from their environment (Mann et al., 2007; Williams, Davids & Williams, 1999). Mann and colleagues (2007) conducted a meta-analysis including 42 studies that examined visual search behaviours between expert and non-expert athletes. They found that expert athletes use fewer fixations of longer duration to extract relevant information from their environment. It is thought that this technique is used to allow for a longer period to extract task relevant information (Mann et al., 2007). Therefore, when developing a more ecologically valid test to track recovery following concussions, cognitive processes of attention, visuospatial working memory and gaze behaviours should be of primary importance to evaluate recovery and help predict when an athlete is able to return to play safely.

### 2.7 Auditory Processing

Auditory processing is a multi-component system that helps humans process and interpret sounds from their environment. The American Speech-Language-Hearing Association (2006) uses the term ‘central auditory processing’ to describe how humans effectively utilize auditory information for further processing by the central nervous system. Central auditory processing includes a variety of auditory processes located in the central nervous system that allow humans to localize, recognize, and discriminate tones. For this thesis, discrimination is of prime importance as participants must effectively process tones and provide an accurate response. To do so correctly, participants need to respond to the correct tone frequency by discriminating between a high tone (1000Hz) and a low tone (375Hz).

Current research has shown that healthy individuals create a phenomenological–spatial association for the frequency of auditory tones (Hansen, Gonzalez & Lyons, 2013) which can help with tone discrimination. In most cases, humans often place tones on a spatial continuum located in a vertical dimension and define them as “high” or “low” (Pratt, 1930; Hansen, Gonzalez & Lyons, 2013) opposed to “close” or “far”. Although tones can be presented from the same location in space, discrimination commonly takes place on a vertical continuum; yet, the understanding for this representation is not fully understood (Pantev et al., 1995). Since humans create a spatial representation of tones, we would expect that the visuospatial sketch pad and central executive to play a valuable role in the discrimination of auditory information. Therefore, the central executive and visuospatial sketch will play a vital role in a dual-task paradigm that includes visuospatial working memory and tone discrimination.

## Section 3: Effects of Concussions

### 3.1 Concussions and Working Memory

Currently, visual and verbal working memory are the main components of the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT), which is one of the most recognized concussion tests. The rationality for evaluating working memory after concussions is due to its location in the frontal lobe which places it vulnerable to the coup and contre-coup abuse caused by biomechanical forces (Clay, 2013; Mattson & Levin, 1990). After all, concussions result from biomechanical forces that commonly cause injury to the frontal lobe area of the brain that supports working memory function (DeHaan et al., 2007; Lee et al., 2008). Furthermore, working memory plays an important role in team sport athletes as it allows them to store and recall relevant information from their dynamic environment. Therefore, it is important that working memory continues to be studied when assessing the long-term effects of concussions.

Sports related concussions have been shown to cause deficits on numerous neuropsychological tests, including the Trail-Making Test, Wechsler digit span test, and Stroop color word test (Guskiewicz, Ross & Marshall, 2001; McDowell, Whyte & D’esposito, 1997). A main outcome for participants with concussions on these neuropsychological assessments are impairments in working memory (Kumar et al., 2013; Iverson et al., 2006) and attention (McDowell, Whyte & D’esposito, 1997; Van donkelaar et al., 2005). For example, Kumar and colleagues (2013) studied 60 participants, 30 with a previous mTBI in the past six months, on a variety of neuropsychological tests examining visual and verbal working memory. The results indicated that participants with an mTBI scored significantly lower on the visual and verbal memory index compared to the healthy participants. Evidence from Kumar and colleagues (2013) is consistent with previous literature (McDowell, Whyte & D'esposito, 1997; Iverson et al., 2006) that both visual and verbal working memory are impaired after mTBI. The reason for working memory deficits may be due to impairments in the executive control system as working memory is largely dependent on executive functioning in cognitively demanding tasks. For that reason, working memory has provided a valuable source of information in participants with concussions and should continue to be examined in future neuropsychological assessments.

### 3.2 Concussions and Attention

Attention difficulties are frequently reported in individuals with concussions (Bernstein, 2002; Cicerone, 1995; Halterman et al., 2006; Howell et al., 2013 Stuss et al., 1989), as participants have trouble allocating attention to complex tasks. Furthermore, attention deficits are commonly a cause from damage to areas affecting the executive functioning component of attention. The executive function system allows for the processing of relevant information while ignoring irrelevant stimuli (Peterson & Posner, 2012; Van Donkelaar et al., 2005). This process can then choose an action plan to complete the desired goal. In recent literature, the executive function has been explored to differentiate concussed participants from healthy controls (Bernstein, 2002; Howell et al., 2013; Howell, Osternig, Koester, Chou, 2014) and future studies should use of this approach due to its vulnerability to injury.

In individuals with mTBI, executive functions are often affected as these individuals have problems properly allocating attentional resources while completing multiple tasks (Cicerone, 1989; Bernstein, 2002; Halterman et al., 2006; Howell et al., 2013). For example, Howell and colleagues (2013) examined the executive function component of attention by conducting an experiment using the Attentional Network Test and Task-Switching Test. The executive function of the Attentional Network Test was measured by comparing the reaction time differences of an arrow stimulus with congruent flankers and incongruent flankers. The Task Switching Test examined executive functioning through a switch cost associated with congruently or incongruently responding to visual stimuli. Howell and colleagues (2013) found longer reaction times in the Attentional Network Test and a significant reaction time cost in the Task Switching Test in participants with a concussion compared to healthy controls. This provides evidence that participants with concussions have trouble properly allocating attentional resources to cognitively demanding tasks; therefore, a dual-task paradigm may be useful to identify long-term deficits and to track concussion recovery.

### 3.3 Concussions and Dual-tasking

Another effective way to examine attention deficits after concussion is through the use of a dual-task paradigm. Of the many literature reviews on concussions (Register-Mihalk, Littleton & Guskiewicz, 2013; Dziemianowicz, 2012; Maruta et al., 2010; Bernstein, 1999), most indicate that the neuropsychological tests that commonly distinguish healthy controls from those with concussions are tasks that place a large demand on information processing resources (Bernstein, 2002; Pellman et al., 2004; Iverson, 2005). One method to increase task demands and tax the central executive system is to use a complex dual-task paradigm. For example, Park, Moscovitch and Robertson (1999) studied attention and working memory in participants with severe traumatic brain injury (TBI). Participants completed a variety of working memory tasks, including consonant trigrams (i.e. C D F), word span and alpha span). Furthermore, a divided attention task was completed that included the paced auditory serial addition task (PASAT) and letter recall task requiring working memory. They found that participants with TBI performed significantly worse on all working memory tasks as well as dividing attention between the paced auditory serial addition task and letter recall task. These findings indicate that working memory, executive functioning, and the ability to dual task is severely affected after a concussion. This research provided evidence to use when examining concussions (a form of mild TBI).

Other research has used the dual-task paradigm to examine participants with concussions. For example, Bernstein (2002) used a complex dual-task paradigm that included visual discrimination between shapes (circles & squares) and two tone discrimination (2012Hz & 1000Hz). Bernstein hypothesized that this method will place a large demand on information processing resources and cause deficits in the performance in participants with a history of concussion. Bernstein (2002) concluded that participants with a history of concussion performed more poorly then healthy controls on each task when the tasks were paired together as opposed to being performed individually. These findings indicate that concussions produce long term impairments in the ability to process information between multiple tasks. Therefore, complex dual-task paradigms appear to be sensitive in identifying persistent deficits in participants with a history of concussion. Since cognitive deficits in attention and memory are frequently reported (Halterman et al., 2006; van Donkelaar et al., 2005; Park, Moscovitch & Robertson, 1999), it is important that these areas continue to be assessed using a dual-task paradigm.

### 3.4 mTBI and Gaze Behaviours

Gaze behaviours are commonly assessed using an eye tracker which measures saccades, number of fixations, fixation duration, and smooth pursuit. Of these measures, saccades, number of fixations, and fixation duration appear to be most helpful to an athlete’s performance because expert athletes perform less saccades with longer fixation durations compared to non-athletes (Mann et al., 2007). It is hypothesized that these measures are different in elite athletes compared to novices and amateurs. In a meta-analysis by Mann and colleagues (2007), visual gaze behaviours were examined between expert and non-expert athletes in sport specific skills. They found that expert athletes used fewer fixations of longer duration, thus indicating that fewer saccadic eye movements help sport specific skills. It is thought that fewer fixations of longer duration allow athletes to extract more task-relevant information which results in more accurate performance outcomes. Examining gaze behaviours have become important in determining successful performance in elite athletes, thus, should be assessed following a concussion because concussions may cause deficits in these behaviours which may affect performance and put athletes a risk for injury.

A relatively new test that has been reported to examine rapid eye movements is the King-Devick test. The King Devick test is a rapid number naming task that examines saccadic eye movements and attention (Galetta et al., 2013). In the few studies conducted on the King-Devick test (Galleta et al., 2013; Galleta et al., 2011) reports have shown that it is a useful sideline test that should accompany other assessments such as the Sideline Concussion Assessment Tool (SCAT). Galleta and colleagues (2013) examined 27 professional hockey players at two time points: pre-season baseline testing and immediately after a concussion. They found that concussed participants took significantly longer to report the numbers compared to pre-season baseline testing (Galetta et al., 2013). These results show that concussions cause impairments to the neural networks responsible for controlling saccades and directing attention. Eye movements are most likely affected by concussions because the neural networks responsible for controlling saccades are mainly located in frontal lobes which are prone to concussive injuries. Past research has shown (Heitger, Anderson & Jones, 2002) that the pathways responsible for making eye movements share similar pathways with working memory which is often affected by concussions (Dehaan et al., 2007; Lee at al., 2008; Clay, 2013). Since these two mechanisms share similar pathways, deficits may be seen in both areas after a diagnosed concussion, thus, eye movements should be examined following a concussion.

Different types of eye movement behaviours have been examined in people who have suffered a concussion, including smooth pursuit (Suh et al., 2006), anti-saccades (Heitger et al., 2009) and memory-guided saccades (Heitger et al., 2009). For example, Suh and colleagues (2006) examined the ability to track a moving target effectively (smooth pursuit) through a circular target tracking task. The target stimulus moved at a rate of 0.40 Hz in a clockwise direction of $7.0^{o}$ radius. Smooth pursuit was evaluated using two methods, including target gain which was defined as the distance between eye location and target velocity, and the number of saccades performed while tracking the target. Position error was examined through the average difference in vertical and horizontal distance between eye and target position. They found that smooth pursuit eye movements were affected in participants with a history of concussion as more saccades and larger eye position errors resulted in a worse ability to accurately track the target.

Further research (Heitger et al., 2009) found that participants with a history of concussion performed significantly worse on a similar smooth pursuit task as well as anti-saccades and memory-guided saccades. Heitger and collegues (2009) studied 72 participants (36 with a history of concussions) on anti-saccades (looking in the opposite direction of a target) that appeared at $5^{o}$ and $15^{o}$ and memory-guided saccades (performing a four step memorized sequence). Additionally, Heitger and colleagues (2009) completed numerous neuropsychological tests, including the Trail-Making test, Auditory Verbal Learning test, Stroop test and Wechsler logical memory test. Anti-saccades were examined using gain of final eye position and number of directional errors. Memory-guided saccades were examined using number of saccades made and number of directional errors. Heitger and colleagues (2009) found that participants with a history of concussion had a significantly higher number of directional errors on anti-saccades and memory guided saccades. Furthermore, participants with a history of concussion had a larger final position error on anti-saccades (10% difference) and a higher number of saccades in memory guided sequences. In addition, neuropsychological tests showed significant differences on tests of executive functions between the two groups. This research (Heitger et al., 2009; Sug et al., 2006) provides evidence that oculomotor control is impaired in participants with a history of concussion relative to documented impairments in neuropsychological tests.

It is evident that eye movements continued to be impaired in participants with a history of concussion. After all, it is hypothesized that oculomotor impairments will affect cognitive functions such as visuospatial information processing and short-term spatial memory because eye movement impairments may cause problems locating and encoding stimuli in the environment (Heitger et al., 2009). Therefore, eye movements should be used as a method to examine concussions.

### 3.5 Research Limitations

Concussions are a widely researched topic and continue to be an interesting subject in neuroscience. Most research on concussions (Register-Mihalik, Littleton & Guzkiewicz, 2013; Berstein, 2002; Van Donkelaar et al., 2005) has focused on divided attention tasks assessing executive functions and working memory. Other areas of research have focused on examining eye movement behaviours after a concussion (Dehaan et al., 2007; Suh et al., 2006; Heitger et al., 2009). Both of these research methods have shown promising results in diagnosing, tracking and identifying the long-term effects of concussions. Evidently, participants with a history of concussion perform worse on cognitively demanding tasks that require dividing attention or making specific eye movements. To our knowledge, pairing the two methods has seen little investigation and thus, may be the most effective way to assess concussion recovery. Therefore, dual-task assessment that involves dividing attention between two complex tasks while evaluating eye movement behaviours could be a promising new area for research

### 3.6 Research Questions:

1. Do concussions cause persisting impairments in executive functions?
2. Do current clinical neurocognitive tests for concussion discriminate athletes with and without a history of concussion?
    a. How do current tests compare to our experimental dual-task paradigm?
3. Do athletes with a previous history of concussion use different gaze behaviours when performing a visuospatial encoding task?
    a. Do gaze strategies change as a function of task difficulty?

### 3.7 Objectives

The goal of this thesis was to investigate executive functions in athletes with and without a history of concussion using a dual-task paradigm. This thesis includes one study with three parts that are interested in evaluating the listed objectives:

Part 1: To compare athletes with and without a history of concussion using an experimental visual-auditory dual task paradigm

- To examine executive function abilities between the sample groups (i.e., concussion, no concussion)

Part 2: To compare performance on the experimental dual-task paradigm to current clinical neurocognitive tests for concussions, specifically the **I**mmediate **P**ost **C**oncussion **A**ssessment and **C**ognitive **T**esting (ImPACT)

- To examine the ability of ImPACT composite scores and experimental measures for predicting concussion history

Part 3: To examine gaze strategies used to encode visuospatial information between the two groups (i.e., concussion, no concussion)

- To investigate the effects of previous concussions on gaze strategies
- To examine gaze behaviours in dual-task situations requiring more cognitive resources

**Section 4: Part One**

**4.1 Introduction**

Concussions have become an epidemic in sports and recreation as an estimated 1.6 to 3.8 million concussions occur annually in the United States (Daneshvar, Nowinski, McKee, & Cantu, 2011). One important goal of concussion research is to develop a better understanding of the acute (hours to weeks) (Broglio, Macciocchi, Ferrara, 2007; Iverson, Gaetz, Lovell & Collins, 2004; McCrea et al., 2003; McClincy, Lovell, Pardini, Collins & Spore, 2006; Van Donkelaar et al., 2005) and long-term (months to years) (Bernstein, 2002; Cicerone, 1995; Howell, Ostering, Van Donkelaar, Mayr and Chou, 2013; Stern et al., 2011) deficits post injury. It is important to develop such an understanding to assist with development of sensitive sideline diagnostic tools and protocols for athletes returning to competition. To date, most research has concentrated on examining acute deficits following a concussion (Broglio et al., 2007; McClincy et al., 2006; McCrea et al., 2003). A variety of impairments have been reported in the acute stage, including memory loss (Echemendia, Putukian, Mackin, Julian & Shoss, 2001; Guskiewicz, Ross & Marshall, 2001; Schatz, Pardini, Lovell, Collins & Podell, 2006), difficulties with orienting and dividing attention (Halterman et al., 2006; Howell et al., 2013; Van Donkelaar et al., 2005), decreased processing speed (Guskiewicz et al., 2001; Schatz et al., 2006), changes in balance control or gait patterns (Catena, van Donkelaar & Chou, 2007; Guskiewicz et al., 2001; McCrea et al., 2003), and even mood disturbances (Chaput, Giguère, Chauny, Denis & Lavigne, 2009; Kontos, Covassin, Elbin & Parker, 2012). In contrast, relatively fewer studies have examined the long-term effects of concussion; therefore, we do not know much about the neurocognitive impairments that may persist months to years after an injury (Bernstein, 2002; Cicerone, 1996; Howell et al., 2013).

The few research studies that have examined long-term consequences of concussion(s) have shown that significant deficits may persist; furthermore, these deficits were not detected by standard clinical neurocognitive tests (Bernstein, 2002; Broglio et al., 2007; Cicerone, 1996; Howell et al., 2013). One persistent deficit that has been reported in people with a history of concussion is an impairment in executive functions (Howell et al., 2013). Executive functions refer to cognitive processes responsible for organizing and executing goal directed behaviours (Anderson, Jacobs & Anderson, 2011), such as planning and completing tasks that require attention, working memory and inhibition of pre-potent responses (Chan, Shum, Toulopoulou & Chen, 2008; Peterson & Posner, 2012). It has also been suggested that executive functions play an important role in a team-sport athlete's competitive abilities as these athletes require attention and working memory to process large amounts of sensory information during dynamic game situations (Vestberg, Gustafson, Maurex, Ingvar & Petrovic, 2012). Since executive functions are often affected in people with concussions, it is important to determine if team-sport athletes with a history of concussion have persistent deficits. The presence of such deficits could have negative consequences and impact their ability to process sensory information in a fast-paced, dynamic game situation, which in turn may lead to a greater risk of injury.

Previous studies used a variety of experimental paradigms to assess executive functions; however, dual-task/ divided attention paradigms are thought to be a more sensitive method (Chan, Shum, Toulpoulou & Chen, 2008; Vestberg et al., 2012). Research with participants with a history of concussion has shown that they have more difficulty with dual-tasks and show greater decrements in performance compared to subjects with no reported concussions (Bernstein, 2002; Catena, van Donkelaar, & Chou, 2009; Cicerone, 1996; Kleffelgaard, Roe, Soberg, & Bergland, 2012; Martini, 2011). For instance, Bernstein (2002) studied 23 participants on a dual-task paradigm that required simultaneous processing of visual and auditory input. Of the 23 participants, 13 had a history of at least one concussion that occurred between one and sixteen years ago. The dual-task paradigm used an auditory tone discrimination task and a visual shape discrimination task. The results showed that participants with a history of concussion had greater difficulty accurately responding to the tone discrimination task in the dual-task condition compared to non-concussed controls; however, no differences were detected between the two groups when each task was performed alone. Other studies have also reported persistent post-concussion deficits in executive functions. For example, Halterman et al (2006) and Howell et al (2013) found significant deficits on the executive component of the Attentional Network Test (ANT) and Task-Switching Test (TST) at 30 and 60-days following a concussion. The results showed that participants with a concussion had deficits in processing relevant information while ignoring irrelevant stimuli (Halterman et al., 2006; Howell et al., 2013). Thus, executive functions, which play an important role in properly allocating attentional resources to relevant stimuli while inhibiting irrelevant information, appear to be affected by concussions. Overall, cross-sectional research has shown that long-term impairments in executive functions is associated with a history of concussion.

Currently, our understanding of the effects of concussions in athletes is incomplete. Past research examining subjects with a history of concussion has studied participants that suffered a brain injury from a fall, motor vehicle/ bicycle accidents or fight/assault (Bernstein, 2002; Cicerone, 1996). Thus, results from this research may not be directly generalizable to athletes because athletes develop a distinct set of cognitive abilities (i.e., executive function skills) that separate them from the general population (Vestberg et al., 2012). For example, expert team-sport athletes have been shown to perform better than non-athletes on tasks requiring executive functions such as response inhibition and problem solving. More recent research (Howell, Osternig, Koester, & Chou, 2014; Howell et al., 2013) has examined sports-related concussions in high school athletes up to 2 months post-injury. However, these results may not be generalizable to collegiate athletes with a history of concussion given that age has been associated with a reduction in the overall effects of concussions (Dougan, Horswill, & Geffen, 2014). Moreover, this research has studied participants up to 2 months post-injury, and long-term impairments have not been studied in athletes with a history of concussion. Therefore, there is a gap in the literature examining executive functions in collegiate athletes with a history of concussion greater than 2 months.

Therefore, the objective of the current study was to investigate the long-term consequences of concussions on executive functions in a homogenous sample of university hockey players which included athletes with and without a history of concussion. To investigate executive functions, we used a dual-task paradigm which required visuospatial working memory (i.e., Corsi block test) and divided attention to discriminate the frequency of an auditory tone. Our main hypothesis was that athletes with a history of concussion will have a significant performance cost for that task that was not instructed to be prioritized (i.e. the tone discrimination task) in the dual-task condition compared to athletes who did not have a history of concussions. It was also hypothesized that no differences would appear on Corsi block test performance between concussion history or task condition because this was instructed to be prioritized.

## 4.2 Methods

### 4.2.1 Participants

Twenty-nine intercollegiate varsity hockey players completed the study (15 females, age *= 19.1 ± 1.26* years old; 14 males, age *= 22.25 ± 0.*9 years old*).* All participants completed the University of Waterloo health history questionnaire that asked questions regarding history of concussion and involvement in sport. A symptom checklist that included 22 questions representing somatic (headache, fogginess), cognitive (memory, concentration), and emotional (sadness, nervous) areas was completed using a six-point Likert scale ranging from none (0) to severe (6). Concussion was defined according to McCrory et al. (2013) as a complex neurological disturbance affecting the brain, resulting from a direct or indirect impact to the head. Presence of a history of concussion was determined based on a brief interview involving questions concerning a previous physician diagnosis, and description of the head injury event. In addition, two self-report questionnaires were administered on different dates to assess self-report reliability. Eighteen athletes reported that they were diagnosed with at least one concussion based on the interview and event description. The time since last concussion ranged from 2 to 98 months *(M =33.5 months).* The sample included 9 athletes with a history of one concussion, 7 athletes with two previous concussions, and 2 athletes with three previous concussions. The study's protocol was approved by the University of Waterloo Research Ethics Board Committee.

**Table 4.1:** Participant characteristics

| **Concussion History** | **N** | **Age (M ± SD)** | **Years of Sport Played** | **Number of Concussions** | **Time Since Injury (mos.)** | **Symptom Checklist Score (max=132)** |
|---|---|---|---|---|---|---|
| **No-Concussion** | 11 | 20.0 ± 2.1 | 14.8 ± 2.5 | - | - | 2.5 ± 3.7 |
| **Concussion** | 18 | 21.4 ± 2.2 | 15.5 ± 3.3 | 1-3 | 33.6 ± 29.7 | 2.6 ± 4.1 |

### 4.2.2 Materials and Procedure

The experiment was a blocked design protocol which consisted of a single auditory tone discrimination task, a single visuospatial working memory task, the Corsi block test (Corsi, 1972), and a combined dual-task condition. Testing protocol took approximately 15-20 minutes and all participants completed the same protocol sequence.

Two computer systems were used to collect data. The visual stimuli were presented on a 19 inch Viewsonic CRT monitor (resolution 1024x768, refresh rate 85 Hz). Auditory tones were generated by a Lenovo computer (Psychtoolbox) and presented using Koss HD-50 computer speakers. Participants sat in an adjustable-height computer chair and head movements were restricted using a chin rest.

The testing protocol began with the auditory tone discrimination task (Auditory Single - Baseline). Participant's head was stabilized in a chinrest located 80cm from a computer monitor which displayed a central fixation cross. Participants were then given an iteration of high tones (1000 Hz) and low tones (375 Hz) and asked to discriminate between the two frequencies. All participants responded that they could accurately discriminate the two tones. Testing collection began with a random presentation of high and low tones that required participants to respond using a mouse with their left hand, with a double click for a high tone and single click for a low tone. A total of seven levels with two trials per level were included in the tone discrimination task. The first level began with four tones (level 1) and consecutively increased up to a maximum of ten tones (level 7). Participants completed all 7 levels of the auditory task which served as a baseline measure (Auditory-Single1).

The second task was the Corsi blocks test (Corsi, 1972), which was computerized using E-prime software (v1.2) and presented on a computer monitor (Visual Single). As illustrated in Figure 4.1A, the visual stimuli (i.e., Corsi blocks) were eight blue squares (8mm x 8mm) presented on a white background with block locations similar to the original layout of the Corsi block test (Corsi, 1972). A fixation cross was located at the centre of the computer screen. Testing began when a block changed colour from blue to red and remained illuminated for 750ms until the next block in the sequence changed colour. Once the sequence was completed, participants were instructed to recall the location of the blocks that changed color by clicking a mouse cursor on the blocks in the order of their appearance using a standard computer mouse with their right hand. All recall trials began with a click on the central fixation before recalling the first target to control starting location across participants. A total of 7 levels were tested, which were defined by the number of blocks that changed color. The first level began with a sequence of two targets (i.e., 2 blocks changed color), and the number of blocks increased with each subsequent level up to a maximum of eight blocks. Participants received two trials per level with each trial presenting a different block sequence. The Corsi test terminated when participants achieved the highest level or if they inaccurately recalled two trials at the same level.

The third task involved completing both tasks simultaneously (Vis-Aud Dual: as shown in Figure 4.1B). Participants had to discriminate the frequency of auditory tones while the Corsi block sequence was presented simultaneously. The tone discrimination task was performed only during the acquisition (i.e., when participants were presented with the sequence) and not during the recall phase of the Corsi block test. Participants were told to focus on the Corsi block test in the dual-task condition.

Figure 4. 1A

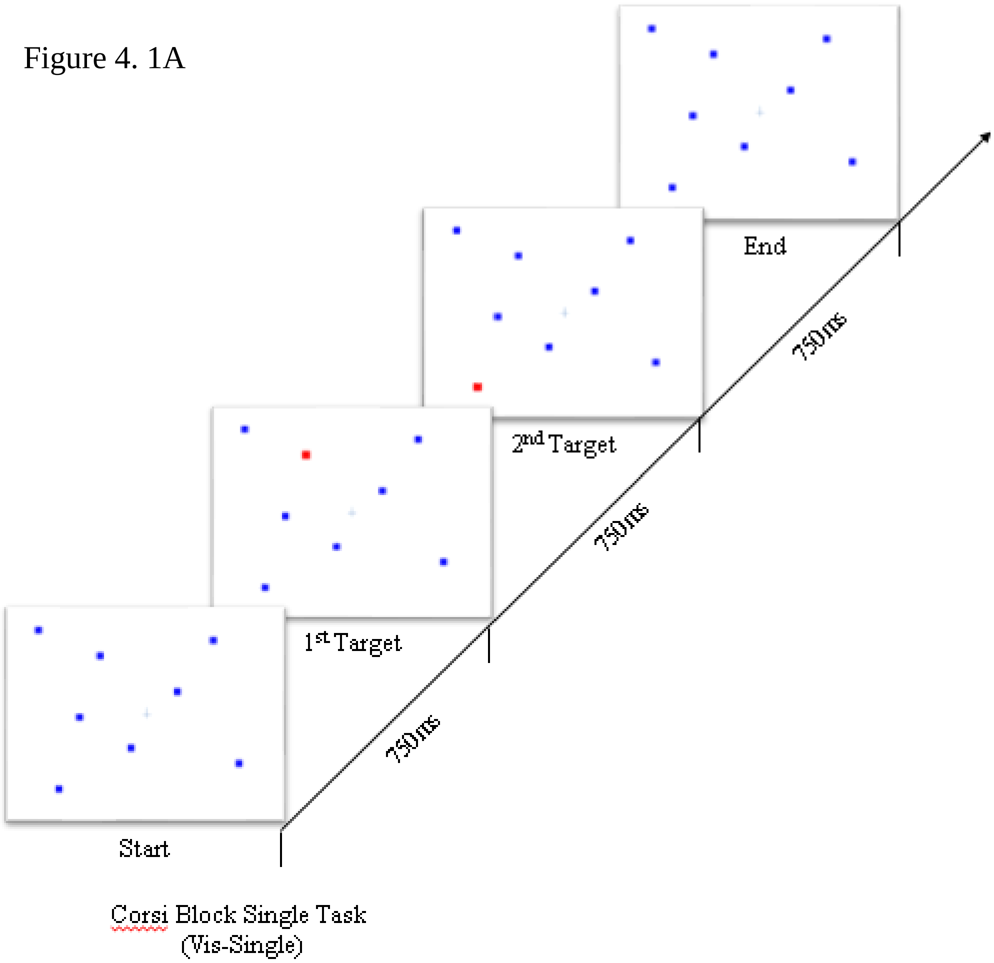


**Figure 4.1A:** Schematic diagram illustrating the Corsi block test sequence of events in the single task condition (A [Vis-Single]) and the dual task condition (B [Vis-Aud Dual]). Each trial began with a presentation of all blocks, shown in blue. During the acquisition phase, a sequence of blocks was highlighted, one block at a time for 750ms (indicated in red colour).

Figure 4.1B

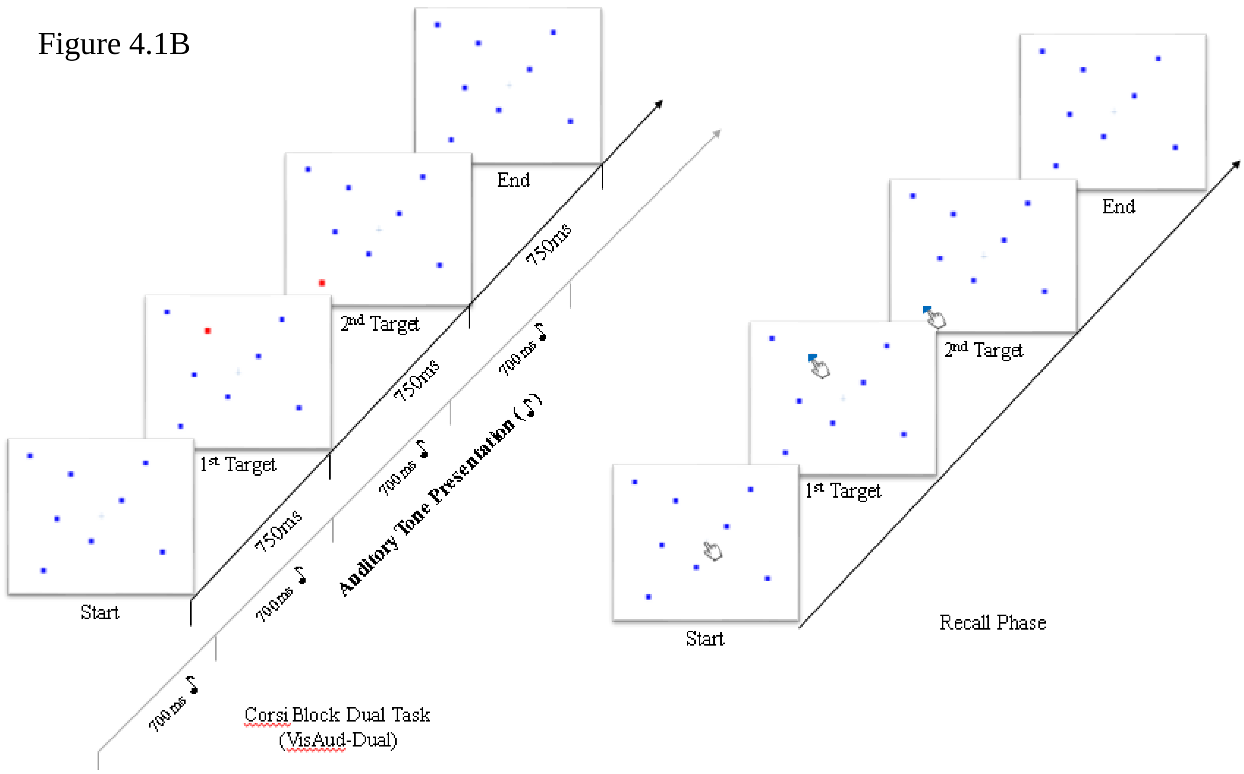


**Figure 4.1B:** Schematic diagram of dual-task events (left figure) and Corsi block recall phase (right figure).

In the final phase of the experiment, participants completed the auditory tone discrimination task again. During the second completion of the tone discrimination task, the auditory tones were matched for the auditory tone level achieved in the dual-task condition. For instance, if a participant achieved level 5 on the Corsi block test in the dual-task condition then their auditory tone discrimination task also terminated at level 5. Only the tone discrimination accuracy during the second single (Auditory-Single2) administration was used to compare performance between the single and dual-task conditions. The second tone discrimination task (Auditory-Single2) was used ensured that the total number of tones presented in the single and dual task conditions were equivalent. The complete testing protocol procedure is outlined in Figure 4.2.

Figure 4.2

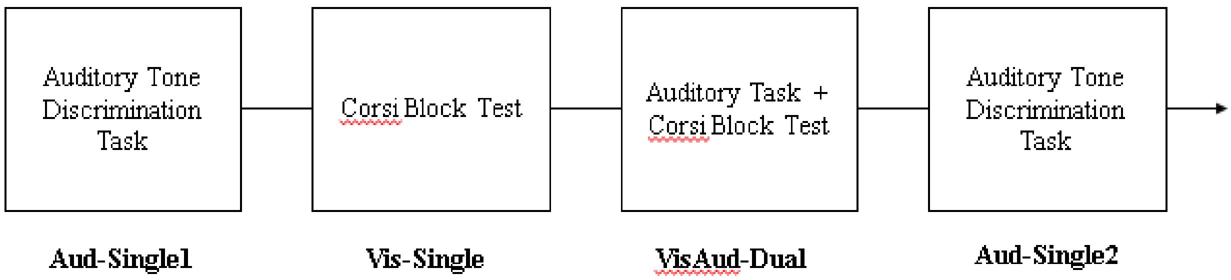


**Figure 4.2**: Testing procedure completed by each participant. The experimental design consisted of 4 blocks of trials: single auditory, single visual, visual-auditory dual, and single auditory.

### 4.2.3 Data Analysis

The Corsi block test and tone discrimination task analyses were completed using E-prime software (v1.2) and Microsoft Excel (MS Office 2013). Data exported from E-prime included: Corsi block target coordinates (mm) and participant's target response selection (i.e., which targets were selected by the participant). Target coordinates were used to determine recall accuracy of the Corsi block sequence.

For the tone discrimination task, accuracy was defined as the percentage of tones correctly responded to in the second administration of the tone task (Auditory-Single2). Tone discrimination accuracy was the main outcome used to compare performance between the single and dual task conditions. Tone discrimination accuracy was also used to determine auditory task cost, which was defined as the difference in performance between tone discrimination accuracy in the single-task condition compared to tone discrimination accuracy in the dual-task condition.

Since we had participants complete the same number of trials in the single-task condition (Auditory-Single2) as they did in the dual-task condition (Vis-Aud Dual), the total number of tones presented in the two conditions (i.e., single, dual) was equal. The number of trials differed between-subjects based on their dual-task performance. The auditory task cost was calculated and converted to a percentage. A higher dual-task cost (%) is associated with a poorer performance in the dual-task condition compared to single-task condition.

A dual task cost equation developed by Beurskens and Bock (2012) was used to evaluate the cost associated with the performance of each task (Corsi memory span and tone discrimination) between conditions (single vs. dual). Dual-task cost was calculated according to the following formula: (**D** represents performance accuracy in the dual task condition; **S** represents performance accuracy in the single task condition).

$$\mathbf{DTC\ (\%) = D - S / S}$$

Corsi block memory span was calculated using two different methods. First, memory span was calculated using the number of correct trials recalled divided by the total number of sequences possible (i.e., maximum 14 trials). This was the initial method used by Corsi (1972) to represent memory span; however, some studies use span length to represent memory span (Kessels, Van Zandvoort, Postma, Kappelle, & De Haan, 2000; Vandierendonck, Kemps, Fastame, & Szmalec, 2004). Span length has been defined as the level at which subjects incorrectly recall both trials of the Corsi sequence minus one (n-1) (Berch, Krikorian & Huha, 1998). In our experiment, both methods were explored as a means of representing memory span; however, no differences were shown between the two methods. Thus, we chose to use the original method (i.e., percentage of trials recalled) presented by Corsi (1972).

### 4.2.4 Statistical Analysis

A two-sample t-test was conducted to determine if the frequency of post-concussion symptoms was different between the two groups (non-concussed vs. history of concussion). A paired t-test was conducted using both administrations of the tone discrimination task (i.e., Auditory-Single1 vs. Auditory-Single2) to test the reliability of the task. A 2-way analysis of variance (ANOVA) was conducted on the dependent variable Corsi block memory span (i.e., % of trials). The between-subject predictor variable was Concussion History (no concussion, concussion). The within-subject variable was Task (single, dual).

The main hypothesis of this research was tested using a 2-way mixed ANOVA with tone discrimination accuracy (%) as the dependent variable. The between-subject factor was Concussion History (no concussion, concussion), and the within-subject variable was Task (single, dual). Since the tone discrimination task was introduced as a secondary task, we expected a larger decrease in performance on this task (i.e., lower accuracy). Significant interaction in the mixed model was further analysed using a Tukey-Kramer post-hoc test to determine which means were significantly different from each other.

Although the sample size was small, a supplementary analysis was conducted using a Spearman correlation to investigate the relationship between auditory cost, number of concussions and time since last concussion. Auditory cost was calculated using the Beursken and Bock (2012) formula. The dual-task cost measure indicates a change in performance between task conditions; thus, a higher cost shows a poorer performance in the dual condition (VisAud-Dual) compared to the single condition (Aud-Single). This analysis was conducted to explore any trends in time since injury or number of concussions affecting tone discrimination performance (i.e., higher cost). For this analysis, data were analysed using two methods. First, a correlation analysis was conducted on all 29 participants. The second method excluded non-concussed participants so the results would not be skewed. The distribution is negatively skewed because non-concussed participants' auditory cost is far below the mean compared to participants with a history of concussion.

### 4.3 Results

The two sample t-test on symptom frequency showed no significant differences between the groups (see Table 4.1). Further analysis showed no significant group differences in somatic, cognitive or emotional symptoms on the health history checklist. This finding was expected because all participants were cleared to participate in their sport, thus, no significant reporting of symptoms should differentiate between the two groups since athletes with a concussion are required to be symptom free before returning to play (McCrory et al., 2013). The paired t-test on the tone discrimination task (Auditory-Single1 vs. Auditory-Single2) showed no significant difference $t$ (28) = .31, $p$ = 0.76, between the two administrations.

The analysis of Corsi block memory span using a 2-way ANOVA revealed no significant effects due to history of concussion or task condition (see Table 4.2). Additionally, there were no significant interactions. The 2-way ANOVA on Corsi block memory span confirmed that participants followed instructions correctly since memory span remained consistent between the single and dual task conditions. Importantly, there was no difference on Corsi block task performance between participants with and without a history of concussion. Since we instructed participants to prioritize the Corsi block test, we expected no differences in Corsi performance between task conditions.

**Table 4.2:** Statistical results for performance accuracy on the Corsi Block test

| Corsi Block Memory Span | | | |
|---|---|---|---|
| **Effects** | *DF* | *F* | *p* |
| Concussion (non-concussed, concussed) | 1, 27 | 0.02 | .88 |
| Task (single, dual) | 1, 27 | 1.85 | .19 |
| Task*Concussion | 1, 27 | 0.10 | .76 |

A 2-way ANOVA on tone discrimination accuracy showed a significant main effect of task (single, dual) $F(1, 27) = 96.71$, $p < .001$. This was an expected result because when two tasks compete for resources, at least one task will suffer in performance (i.e., tone discrimination task). Our main hypothesis that athletes with concussion history will perform worse on the dual task was supported by a significant interaction between task conditions and concussion history ($F(1, 27) = 17.01$, $p < .001$; see Figure 4.3). Post hoc test revealed that participants with a history of concussion had a lower tone discrimination accuracy in comparison to non-concussed athletes in the dual-task condition (Non-Concussed: $M = 78.00\%$, $SD = 8.80$; Concussion: $M = 62.94\%$, $SD = 13.64$). In contrast, there was no difference in tone discrimination accuracy between the groups in the single-task condition (Non-Concussed: $M = 87.91\%$, $SD = 9.01$; Concussion: $M = 87.65\%$, $SD = 4.64$).

Figure 4.3

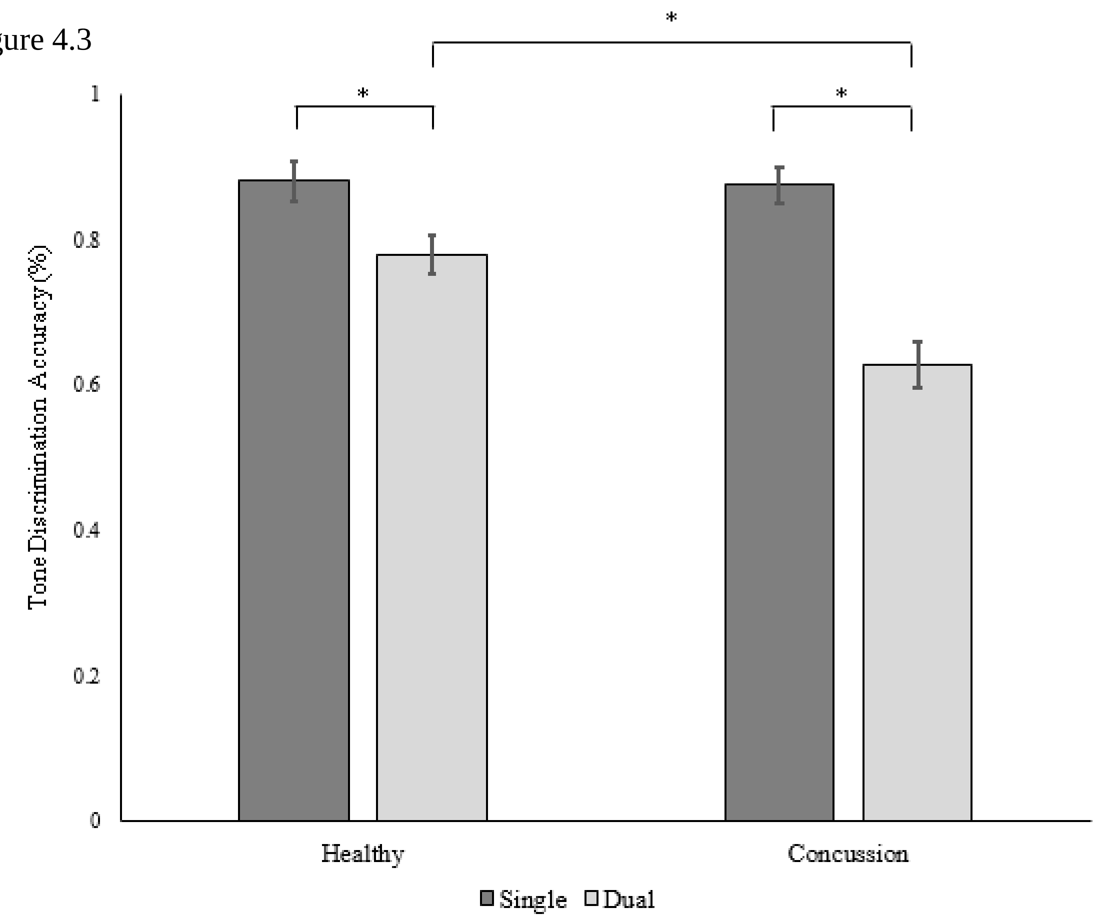


**Figure 4.3:** Mean tone discrimination accuracy obtained during the single and dual task plotted for the two groups of participants (i.e., no concussion, concussion). Participants with a history of concussion had a significantly lower tone accuracy when performing the dual task in comparison to non-concussed participants ($p<0.05$). Error bars represent standard error of the mean.

An exploratory analysis was conducted to examine if concussion history had a differential effect on tone discrimination accuracy for males and females. Our sample included 10 males with a history of concussion, and 8 females with a history of concussion. Since we had very few males without a history of concussion (i.e., n=4), no hypothesis testing could be conducted, instead only the means and standard deviation are presented. The tone discrimination accuracy for each group in the single-task condition was slightly lower in the males (Non-

Concussed: *M* = 80.75%, SD = 10.24; Concussion: *M* = 85.20%, *SD* = 13.43) compared to the females (Non-Concussed: *M* = 92.28%, SD = 4.64; Concussion: *M* = 90.63%, *SD* = 4.92). In the dual-task condition, tone discrimination accuracy was reduced in both groups: males (Non-Concussed: *M* = 70.75%, SD = 10.69; Concussion: *M* = 60.90%, *SD* = 15.62), and females (Non-Concussed: *M* = 82.14%, SD = 4.09; Concussion: *M* = 65.50%, *SD* = 11.17).

Finally, Spearman correlation showed a significant relationship between auditory cost and the number of concussions $r$ (29) = .71, $p$ < .0001. Seventeen out of the eighteen previously concussed individuals fell outside the 95% confidence intervals of the non-concussed participant's mean auditory cost (see Figure 4.4). In contrast, removing non-concussed participants from the correlation analysis resulted in a non-significant relation between auditory cost and the number of concussions $r$ (17) = .16, $p$ = .52, or auditory cost and time since last concussion $r$ (17) = .33, $p$ = .19.

Figure 4.4

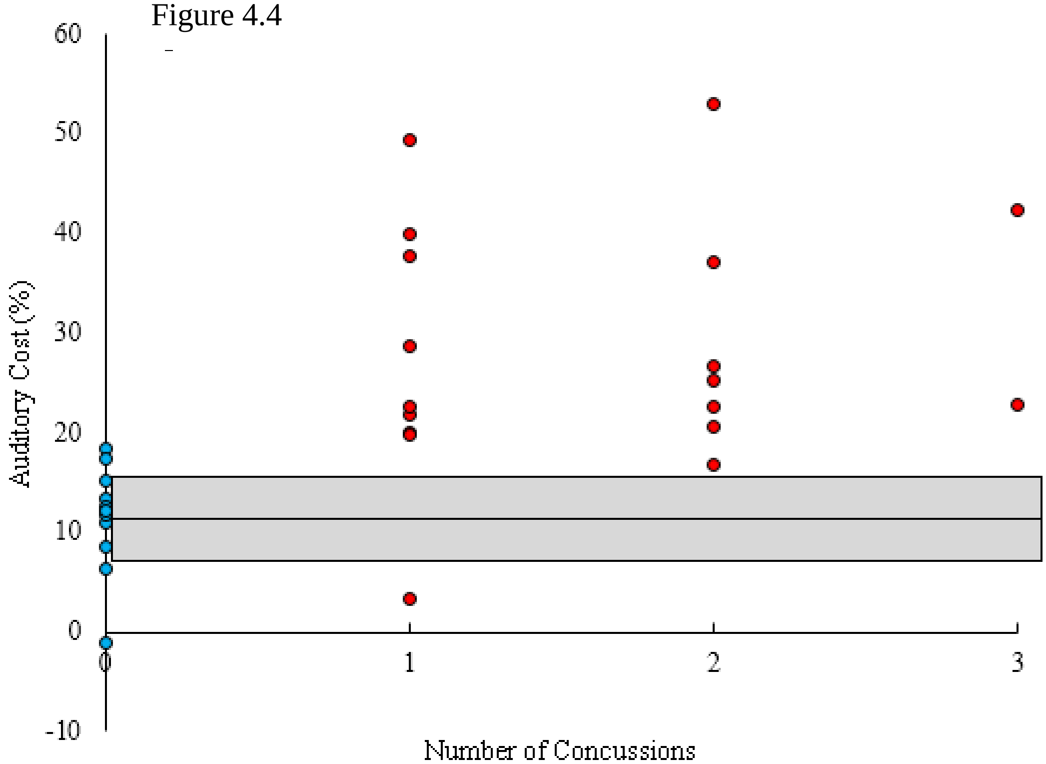

**Figure 4.4:** Individual auditory cost as a function of a number of concussions. Participants without a history of concussions are indicated by the blue symbols and the grey, shaded area indicates the 95% confidence interval for the mean for control participants. Seventeen out of 18 participants with a history of at least one concussion had an auditory cost that fell outside of the 95% confidence interval.

### 4.4 Discussion

To our knowledge, the present study is the first to explore executive functions in a homogenous sample of intercollegiate varsity male and female hockey players with and without a history of concussion. Our study is important because executive functions play a vital role in athlete's competitive abilities, thus, it is necessary to examine how these functions are affected by concussions. Executive functions were assessed using an experimental dual-task paradigm that included the Corsi block test and an auditory tone discrimination task, thus, our experimental paradigm examined two important aspects of executive functions: visuospatial working memory and divided attention. Experimental results showed that athletes with a history of concussion had greater difficulties dividing attention between two tasks compared to their non-concussed counterparts. Importantly, the deficit in performance accuracy was only evident when cognitive resources were stressed during the dual-task condition. In contrast, there was no significant difference between the groups when the visual and auditory tasks were performed alone.

Executive functions is a term used to describe cognitive processes that regulate incoming information to complete goal directed behaviours (Friedman et al, 2008). Executive functions involve several cognitive processes, including: problem solving, response inhibition, multi-tasking, dividing attention, and updating working memory (Chan et al., 2008; Friedman et al., 2008). Recent research has shown that executive functions are important in a team sport athlete's performance because athletes must constantly monitor their environment, and select task-relevant sensory information while inhibiting irrelevant information in order to execute goal-directed behaviours skilfully (i.e., with speed, accuracy and precision) during dynamic game situations (Vestberg et al., 2012). Since executive functions play a critical role in sport performance, it is important to understand how different aspects of executive functions are affected by sports-related concussions.

Our research paradigm required participants to divide attention between two tasks, a process controlled by executive functions. The current results extend previous studies by Bernstein (2002) and Cicerone (1996), who reported that a history of concussions affects one's ability to perform two tasks simultaneously. In contrast to these studies that involved a mixed population of athletes and non-athletes, we examined varsity intercollegiate athletes who must use executive functions to process visual and auditory information quickly (i.e., differentiating teammates from opposition) during dynamic game situations. Thus, our results may have greater generalizability to team-sport athletes; however, further evaluation into game-like tasks involving visual and auditory information should be addressed in future research. Similarly to the finding of Bernstein (2002), we found no relationship between dual-task performance (i.e., auditory cost) and the number of concussions or the time since last concussion; however, small sample sizes may limit the power of our findings. Future research should continue to address this question because there has been some evidence to suggest that the number of concussions is associated with reduced performance on neuropsychological tests (Iverson et al., 2004). Therefore, future research should focus on increasing the sample size of participants with multiple concussions.

More recent research from Howell et al. (2013) reported that executive functions, as measured by the Attentional Network Test and Task-switching test, were significantly impaired in adolescent participants (i.e., 15-17 years) for up to 2-months post-concussion. Since collection occurred at 5 time points (72hrs, 1wk, 2wks, 1 month and 2 months), this research provided insight into the long-term impairments that may persist when concussion symptoms disappear (i.e., 2wks-1month). The persisting impairments in executive functions may suggest that a longer recovery period is needed after a head injury to ensure that athletes are able to return to activity safely. Based on our findings, it appears that a history of concussion may be a contributing factor explaining some of the executive function impairments in our sample. Although participant's history of concussion ranged from months to years ago, their dual-tasking abilities were significantly reduced. Therefore, the potential to perform a discrimination task (attend to the auditory cue in this experiment; attend to a teammates voice in a game) under high cognitive loads for athletes, may be impaired or lowered following a concussion compared to other athletes with no concussions. In our sample, dual task performance in the majority of participants (17/18) with a history of concussion fell outside the 95% confidence interval of the control subjects. Since our research was a cross-sectional design, we do not know if the reduction in executive functions resulted from a concussion or if lower executive functions led to the concussion. It is also possible that athletes with executive function deficits were more inclined to report a history of concussion; however, we believe that our participants did not over-report their history of concussion as many concussions are unrecognized and underreported (Llewellyn, Burdette, Joyner, & Buckley, 2014). In order to address these question, future research should focus on a prospective design to investigate any long-lasting changes in executive functions.

A well-recognized cognitive psychological model we can use to interpret our results is the Baddeley and Hitch's (1974) working memory model. The Baddeley model includes three components that are responsible for storing and manipulating incoming sensory information

(Baddeley, 1992). The central executive control system and the visuospatial sketchpad are two components important to our experimental paradigm. The central executive component is described as an attentional control system that encompasses the operations of executive functions (Baddeley, 1992). In addition, the central executive is responsible for dividing attention between multiple tasks and prioritizing which information is held in the working memory system. In our study, the central executive is responsible for directing attention to process and rehearse the spatial location of blocks in the visuospatial sketchpad. The central executive is also important during the dual-task condition which requires dividing attention between the visual and auditory tasks. Our results suggest deficits in central executive functioning which may be explained by concussion history because most athletes with a history of concussion had more difficulty in dividing attention between the Corsi block test and the auditory tone discrimination task. Importantly, the deficit was only significant when task demands were stressed in the dual-task condition.

Neuroimaging studies have revealed two potential networks responsible for executive functions including, the fronto-parietal control system and cingulo-opercular system (Petersen & Posner, 2012, Sauseng, Klimesch, Schabus & Doppelmayr, 2004). The fronto-parietal control system consists of the dorsolateral prefrontal cortex (DLPFC), superior and inferior parietal lobes and precuneus. The DLPFC is activated in healthy participants when they are completing tasks that require high central executive demands such as updating working memory, dividing attention and multi-tasking (Chein, Ravizza, & Fiez, 2003; Petersen & Posner, 2012, Sauseng, Klimesch, Schabus, & Doppelmayr, 2004; Wager & Smith, 2003). In contrast, research has shown significantly reduced DLPFC activation in participants with a history of concussion when they perform similar tasks (Chen, Johnston, Collie, McCrory & Ptito, 2007; Ptito, Chen &

Johnston, 2007; Sauseng et al., 2004). Overall, neuroimaging studies show that concussions are associated with reduced activation in the DLPFC, thus provide a reasonable rationale for the disruption of cognitive resources controlled by the central executive. The deficits that were shown in our dual task study may be due to a disruption of the cortical network involved in controlling executive functions.

Some of the differences in our sample may also be associated with sex-related effects of concussions. To date, research exploring sex-related effects of concussions has shown mixed results on neuropsychological tests (Broshek et al., 2005; Colvin et al., 2008; Covassin et al., 2006; Covassin, Schatz, & Swanik, 2007). Past research has shown females outperforming males on baseline verbal memory tasks in athletes with and without a history of concussion (Covassin et al., 2006); however, males perform better than females on tasks requiring visuospatial working memory and reaction time (Capitani, Laiacona, & Ciceri, 1991; Colvin et al., 2008; Covassin et al, 2006; Covassin et al., 2007). After a diagnosed concussion, it has been reported that females have decreased simple and choice reaction times, as well as slower processing speeds compared to males (Broschek et al., 2005). Additionally, different recovery patterns have been shown between sexes but most research shows that females typically have longer and more symptomatic recoveries (Colvin et al., 2008; Covassin et al., 2007). To our knowledge, there is no research that has solely focused on examining executive functions in male and female team-sport athletes with and without a history of concussion. Although we did not have enough power to test sex differences, future research should evaluate sex differences after a diagnosed concussion because of the hormonal changes that may affect recovery patterns.

In conclusion, the present research demonstrates the importance of evaluating executive functions in athletes with a history of concussion. Our findings showed that concussions contributed to poorer performance on a dual-task paradigm evaluating executive functions; however, we currently do not know how this relates to an athlete's performance on common neuropsychological tests or their functional performance. Future research should compare performance on clinical neuropsychological tests with performance on dual-task paradigms, such as the one used in our study. Several neuropsychological tests are used to manage sports-related concussions including, the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT), the Cogstate cognitive functioning test and the HeadMinder test. The ImPACT is the most widely used test in professional and collegiate sports for managing concussions (Dziemianowicz et al., 2012; Notebaert & Guskiewicz, 2005). A comparison between the ImPACT and dual-task experiments targeting executive functions may be supportive in ensuring that athletes recover fully before returning to play. Additionally, future research should assess the sensitivity of current neuropsychological tests (i.e., ImPACT) and experimental dual-task paradigms to the long-term deficits that may persist in participants with a concussion history. Therefore, our research has important implications for assessment and management of concussions.

## Section 5: Part Two

### 5.1 Introduction

Concussions can be described as a complex pathophysiological brain injury resulting from a direct or indirect impact to the head (McCrory et al., 2013). In recent years, concussions have received widespread media coverage in professional and amateur sports because of the detrimental effects shown in active and retired athletes (Stern et al., 2011). For example, recent research conducted with athletes from the National Hockey League and Ontario Hockey League reported nearly 6% of players suffering a concussion between 2009-2011, with incident rates rising each year (Donaldson, Asbridge, & Cusimano, 2013). The increasing frequency of reported concussions appears to be associated with greater awareness of concussions among athletes, coaches, trainers and clinicians (Lincoln et al., 2011).

Currently, return-to-play decisions are made based on subjective report and clinical evaluation of symptoms, including a neurocognitive assessment (McCrory et al., 2013). Several studies showed that standard neurocognitive tests provide a sensitive assessment during the acute stages (i.e., 24h – 72h) following concussion; however, assessment measures typically return to baseline 5-10 days post-injury (Broglio, Macciocchi, & Ferrara, 2007; Iverson, Brooks, Collins, & Lovell, 2006a). Moreover, most research has shown that clinical neurocognitive tests are unable to discriminate participants with a previous history of concussion from those with no reported concussions in the long-term (Broglio, Ferrara, Piland, & Anderson, 2006; Maerlender et al., 2010; Iverson, Brooks, Lovell, & Collins, 2006b). These results can be explained by two mutually exclusive possibilities: either concussions do not produce long-term impairments in cognitive functioning or the current clinical tests are not sensitive to the subtle long-lasting changes of concussions (Broglio et al., 2006; Maerlender et al., 2010; Iverson et al., 2006b). Although clinical tests fail to detect neurobehavioural changes in the chronic cases, there is a growing body of literature reporting that long-term deficits in executive functions persist in athletes who suffered a concussion (Berstein, 2002; Halterman et al., 2006; Howell, Osternig, Van Donkelaar, Mayr, & Chou, 2013a; Tapper, Niechwiej-Szwedo, Gonzalez, Roy; 2015). Moreover, a history of multiple concussions has been associated with more serious long-term consequences such as Post-Concussion Syndrome, Alzheimer's disease, Parkinson's disease, dementia, and chronic traumatic encephalopathy (Stern et al., 2011). Therefore, our knowledge about the chronic effects of concussions comes from separate studies using clinical measures and tests examining executive functions; however, no studies have compared clinical measures with executive function tests in the same population.

Several neurocognitive tests are used for assessing concussions including, the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT), the CogState Computerized Tasks for Cognitive Functioning, and the Headminder Concussion Resolution Index Test (Dziemianowicz et al., 2012; Notebaert & Guskiewicz, 2005). Past research has shown the ImPACT to be the most widely used neurocognitive assessment tool by athletic trainers in professional and amateur sports worldwide (Dziemianowicz et al., 2012; Notebaert & Guskiewicz, 2005). The ImPACT is a computerized neuropsychological test used to assess attention, working memory, visuomotor processing speed, and reaction time, and was designed to evaluate cognitive deficits that occur after a diagnosed concussion and assist with return-to-play decisions. To date, most research has shown the ImPACT to be sensitive to the acute (24h to 72h) deficits post-concussion (Broglio et al., 2007; Iverson et al., 2006a; Schatz, Pardini, Lovell, Collins, & Podell, 2006). For instance, Schatz et al. (2006) tested 138 athletes (72 concussed) using the computerized ImPACT. Concussed athletes were tested within 72 hours of a reported concussion and all five composite scores were compared to age and education matched healthy control scores. They found the ImPACT to be 81.9% sensitive for discriminating athletes with and without a history of concussion on at least one of the five composite scores. Similar findings were reported by Iverson et al. (2006a) and Broglio et al. (2007), who reported the ImPACT was a sensitive test for accurately showing deficits on at least one composite measure within 72 hours of a physician diagnosed concussion.

Thus far, research examining the ImPACT's ability to discriminate athletes with and without a history of concussion has failed to detect any long-term difference (Broglio et al., 2006; Iverson et al., 2006b; Maerlender et al., 2010). For example, Broglio et al. (2006) administered the ImPACT assessment on 261 athletes before the 2004 and 2005 seasons. Eighty eight athletes who were cleared to play had a history of at least one concussion before the ImPACT was administered, with the results showing no difference on the ImPACT composite scores between athletes with and without a history of concussion. Broglio et al's (2006) research is consistent with a body of literature (Iverson et al., 2006b; Maerlender et al., 2010) showing that the ImPACT does not detect significant changes in cognitive functioning after the acute phase has resolved in athletes with a concussion compared to participants with no concussion. In contrast, there is evidence from studies of executive functions indicating that concussions may result in long-term impairments that last months to years' post-injury (Bernstein, 2002; Cicerone, 1996; Howell et al., 2013a; Tapper et al., 2015). Moreover, these deficits were detected when participants were required to allocate their attentional resources between two simultaneously presented tasks. Therefore, research has yet to compare the ImPACT to tests of executive functions that appear to be sensitive to long-lasting effects of concussions.

Executive functions is a term used to describe the higher level cognitive processes that regulate thought and action (Anderson, Jacobs & Anderson, 2008). Multiple cognitive processes are encompassed by executive functions including, updating working memory, dividing attention, multi-tasking, inhibiting prepotent responses and cognitive flexibility (Anderson et al., 2011; Chan, Shum, Toulopoulou, & Chen, 2008; Friedman et al., 2008; Petersen & Posner, 2012). Executive functions also play an important role in an athlete's competitive abilities because athletes must process multiple sensory stimuli simultaneously and use the task-relevant information to guide goal directed movements. Previous literature has shown that executive functions can be studied using dual-task/ divided attention paradigms (Chan et al., 2008; Friedman et al., 2008). Moreover, divided attention paradigms appear to be a sensitive method for discriminating athletes with a concussion from those with no prior history (Bernstein, 2002; Cicerone, 1996; Howell et al., 2013a; Martini et al., 2011), as dual-task paradigms require more cognitive resources (Chan et al., 2008; Friedman et al., 2008; Park, Moscovitch, & Robertson, 1999). Therefore, dual-task paradigms may be more sensitive than the ImPACT at discriminating athletes with a history of concussion because dual-tasking stresses information processing resources which may be damaged after a head injury; however, a direct comparison between the IMPACT and performance on a dual task has not yet been examined in the same sample.

The present study compared performance on the ImPACT and the dual-task paradigm in a homogenous group of varsity athletes with and without a history of concussion. Based on previous literature, it was hypothesized that the ImPACT's Verbal Memory, Visual Memory, Visual Motor Speed, and Reaction Time Composite scores would not discriminate athletes with and without a history of concussion. In contrast, our dual-task paradigm has been shown to discriminate athletes with and without a history of a concussion (Tapper et al., 2015). More specifically, the ability of athletes with a history of concussion to perform the secondary (tone discrimination) task in the dual condition came at a higher cost compared to athletes with no history of concussion.

## 5.2 Methods

### 5.2.1 Participants

Participants were 29 varsity collegiate ice hockey players (15 females, age = $19.1 \pm 1.26$ years old; *14* males, age = $22.25 \pm 0.9$ years old). The same 29 participants were evaluated in the previous study (Tapper, Gonzalez, Roy, & Niechwiej-Szwedo, 2015). The University of Waterloo health history questionnaire was administered to all participants and included questions concerning concussion history, sport involvement and symptoms experienced in the past 6 months. Concussion was defined as a change in neurological functioning resulting from a direct or indirect force to the head (McCrory et al., 2013). Participants were diagnosed with a concussion based on a brief interview asking questions regarding a physician diagnosis, their injury event, and post-injury symptoms and feelings. Each participant’s concussion history was documented using two questionnaires on different dates (M= 7 mos. apart) to confirm the reliability of self-reported concussions. In addition, participants completed a 22-question symptom checklist focusing on current somatic (headache, pressure in head), cognitive (trouble remembering, confusion), and emotional (irritability, anxiety) feelings. A six-point Likert scale rated symptom severity from 0 (none) to 6 (severe). Eighteen athletes reported a previous concussion with the number of concussions being reported as follows: one (n = 9), two (n = 7), and three (n = 2). The time since last concussion varied from 2 months to 2 years. All participants were cleared to participate in the study and had returned to full competition prior to their testing date. The University of Waterloo Research Ethics Board Committee approved the experimental protocol.

### 5.2.2 Materials and Procedures

Version 2.0 of the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT Applications, Pittsburgh, Pennsylvania, USA) was administered to all participants before the 2013 or 2014 athletic seasons. The computerized neuropsychological test battery consists of six modules that measure various aspects of cognitive functioning including attention, working memory, reaction time and visuomotor processing speed. Each module test contributes to five composite scores including, Verbal Memory, Visual Memory, Processing Speed, Reaction Time, and Impulse Control. The ImPACT was administered according to the manufacturer's user manual (Lovell, 2012) and took approximately 20-30 minutes to complete.

The detailed experimental protocol is described in Tapper et al (2015). Briefly, participants completed a dual task paradigm. The two tasks included an auditory tone discrimination task, and the Corsi block test. The auditory tone discrimination task involved an iteration of high (1000Hz) and low tones (375Hz). Participants were asked to discriminate between the two frequencies by making a manual response using a computer mouse with their left hand. A total of seven levels with two trials per level were included in the auditory task, with the first level starting with four tones and increasing up to a maximum of ten tones.

The Corsi block test is a computerized neuropsychological test that measures visuospatial working memory. The Corsi layout was similar to the original Corsi block test (Corsi, 1972). A total of seven levels with two trial per level were included in the Corsi test. The first level started with two blocks and increased up to a maximum of eight blocks. The test terminated when participants achieved the maximum level (i.e., level 7) or if they incorrectly recalled both trials at the same level.

Finally, the Corsi block test and the auditory tone discrimination task were completed simultaneously. The auditory task was only performed during the presentation of the Corsi block sequence. Participants were instructed to primarily focus on the Corsi block test in the dual-task condition to allow for easier comparison between individuals and limit the amount of strategies used by different individuals during the dual-task condition.

### 5.2.3 Data Analysis

ImPACT analysis was completed using Microsoft Excel (MS Office 2013). The analysis of data obtained in the experimental tasks (i.e., Corsi test and auditory tones) was completed using E-prime software (v1.2) and Microsoft Excel. Auditory tone data exported from E-prime included: tone sequence order (i.e., high and low sequence) and participant’s tone response type (i.e. single or double click). Corsi block data were also exported from E-prime and included target coordinates (i.e. location on screen) and participant’s coordinates selection in order of response.

Auditory cost was defined as the difference in tone discrimination response performance between single-task and dual-task conditions. Tone response accuracy (i.e., the percentage of correct tones responded to in each task condition) was used to calculate auditory cost. The total number of trials were matched between the single and dual-task conditions (i.e., an equivalent number of tones was administered in the single and dual task condition). Auditory cost was the main outcome variable to compare Concussion History (concussion, no concussion), and was calculated according to the dual-task cost equation developed by Beurskens and Bock (2012):

$$\mathbf{DTC\ (\%) = D - S / S}$$

(**D** symbolises tone response accuracy in the dual task condition; **S** symbolises tone response accuracy in the single task condition).

Corsi block cost was the secondary experimental outcome variable. Corsi cost was calculated as the number of trials correctly recalled between task conditions. The same dual-task cost equation was used to compare Corsi block accuracy. All data analysis were conducted using SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA).

### 5.2.4 Statistical Analysis

The main analysis was conducted to determine if the four ImPACT scores (i.e., Verbal Memory, Visual Memory, Visual Motor Speed, and Reaction Time) or the dual-task measures (i.e. Auditory Cost, and Corsi Cost) could identify the athletes with and without a history of concussion. Two separate logistic regression analysis were performed with Concussion History (i.e. no concussion, concussion) as the dependent variable. The first logistic regression used four ImPACT composite scores as the predictor variables. The Impulse Control composite was removed from the analysis because it is used as a screening score to confirm that no participants intentionally performed poorly on the test to register a low baseline that would be easily achievable after a concussion, otherwise referred to as "sandbagging". The second logistic regression used the dual-task Auditory Cost and Corsi Cost measures as the predictor variables.

A supplementary analysis was performed using a Pearson correlation for each ImPACT composite score and both dual-task measures (i.e. Corsi cost & auditory cost). This analysis was conducted to explore any associations between the two tests.

## 5.3 Results

A logistic regression analysis was conducted to examine whether a history of concussion can be predicted using the ImPACT's Verbal Memory, Visual Memory, Visual Motor Speed, and Reaction Time scores. The full model with the four predictors was tested against an intercept only model, and the results showed no statistical difference $X^2(4, N=29) = 5.49$, $p = 0.240$. Thus, none of the ImPACT scores could differentiate between the two groups (i.e. concussion, no concussion) (see Table 5.1).

**Table 5.1:** ImPACT Logistic Regression

| Predictor | β Estimate | Standardized β Estimate | SE β | Wald's $X^2$ | *df* | *p* | Odds ratio Estimate |
|---|---|---|---|---|---|---|---|
| Verbal Memory | -0.134 | -0.731 | 0.091 | 2.174 | 1 | 0.140 | 0.875 |
| Visual Memory | 0.163 | 1.022 | 0.095 | 2.957 | 1 | 0.085 | 1.177 |
| Visual Motor Speed | -0.082 | -0.297 | 0.103<br>4 | 0.629 | 1 | 0.428 | 0.921 |
| Reaction Time | 0.008 | 0.356 | 0.007 | 1.451 | 1 | 0.228 | 1.009 |
| **Test** | | | | $X^2$ | *df* | *p* | |
| Likelihood Ratio | | | | 5.492 | 4 | 0.240 | |
| Score | | | | 4.442 | 4 | 0.349 | |
| Wald | | | | 3.273 | 4 | 0.513 | |

Next, a logistic regression was conducted to examine if the dual task costs obtained during the performance of our dual-task could differentiate between the athletes with and without a concussion history. The full model, including Auditory Cost and Corsi Cost, was tested against an intercept only model. Results showed that the model was statistically significant $X^2(1, N=29) = 18.52$, $p < .001$. Analysis of the maximum likelihood estimates showed Auditory Cost (p = 0.012) as the only variable contributing to concussion history prediction. The odds ratio indicated that a history of concussion was 1.34 times, 95% CI [1.06, 1.68] more likely in athletes with a high auditory cost compared to those who had a lower auditory cost (see Table 5.2).

**Table 5.2:** Dual-Task Logistic Regression

| **Predictor** | **Estimate** | **Standardized** | **SE Beta** | **Wald's $X^2$** | ***df*** | ***p*** | **Odds ratio Estimate** |
|---|---|---|---|---|---|---|---|
| Corsi Cost | 0.063 | 0.012 | 1.592 | 0.002 | *1* | *0.968* | 1.065 |
| Auditory Cost | 0.290 | 2.119 | 0.116 | 6.316 | 1 | 0.012 | 1.337 |
| **Test** | | | | **$X^2$** | ***df*** | ***p*** | |
| Likelihood Ratio | | | | 18.523 | 2 | <.001 | |
| Score | | | | 11.938 | 2 | 0.003 | |
| Wald | | | | 6.321 | 2 | 0.042 | |

An exploratory analysis was performed to measure the sensitivity and specificity of each test (i.e., ImPACT & dual-task) to discriminate athletes with and without a history of concussion. Sensitivity was defined as the probability that the score will identify an athlete with a previous concussion when a prior concussion was diagnosed. Specificity was defined as the probability that the score will identify an athlete as having no previous concussion when no prior concussion was diagnosed. Since we had a small sample size (n = 29), no hypothesis testing could be conducted. The analysis showed the dual-task paradigm as a more sensitive (94.44%) and specific (63.64%) test for discriminating athletes with and without a history of concussion compared to the ImPACT test (see Table 5.3).

**Table 5.3: Sensitivity and Specificity**

| | Sensitivity | Specificity |
|---|---|---|
| **ImPACT Composites** | | |
| Verbal Memory | 44.44% | 72.73% |
| Visual Memory | 27.78% | 72.73% |
| Visual Motor Speed | 38.89% | 54.55% |
| Reaction Time | 22.22% | 72.73% |
| **ImPACT Total** | **61.11%** | **45.45%** |
| **Experimental Measures** | | |
| Corsi Block Cost | 27.78% | 63.64% |
| Auditory Cost | 94.44% | 72.73% |
| **Dual-Task Total** | **94.44%** | **63.64%** |

Finally a Pearson correlation using each ImPACT composite and both dual-task costs showed a significant relationship between auditory cost and three ImPACT composites including, visual memory composite (r = -.40), visual motor speed composite (r = -.44) and reaction time composite (r = .39) (see Table 5.4).

**Table 5.4:** ImPACT and Dual-Task Correlations

| | **Verbal Memory Composite** | **Visual Memory Composite** | **Visual Motor Speed Composite** | **Reaction Time Composite** | **Impulse Control Composite** | **Corsi Block Cost** | **Auditory Tone Cost** |
|---|---|---|---|---|---|---|---|
| Verbal Memory Composite<br>P-value | - | **0.59**<br>**0.007** | **0.47**<br>**0.009** | -0.29<br>0.122 | -0.32<br>0.093 | 0.10<br>0.571 | -0.13<br>0.491 |
| Visual Memory Composite<br>P-value | **0.59**<br>**0.007** | - | **0.76**<br>**<.001** | **-0.54**<br>**0.002** | -0.34<br>0.072 | 0.20<br>0.275 | **-0.41**<br>**0.028** |
| Visual Motor Speed Composite<br>P-value | **0.47**<br>**0.009** | **0.76**<br>**<.001** | - | **-0.43**<br>**0.021** | -0.35<br>0.067 | 0.19<br>0.301 | **-0.44**<br>**0.016** |
| Reaction Time Composite<br>P-value | -0.29<br>0.122 | **-0.54**<br>**0.002** | **-0.43**<br>**0.021** | - | 0.11<br>0.563 | -0.10<br>0.581 | **0.39**<br>**0.033** |
| Impulse Control Composite<br>P-value | 0.32<br>0.093 | -0.34<br>0.072 | -0.35<br>0.067 | 0.11<br>0.563 | - | 0.06<br>0.748 | 0.32<br>0.087 |
| Corsi Block Cost<br>P-value | 0.10<br>0.571 | 0.20<br>0.275 | 0.19<br>0.301 | -0.10<br>0.581 | 0.06<br>0.748 | - | -0.33<br>0.072 |
| Auditory Tone Cost<br>P-value | -0.13<br>0.491 | **-0.40**<br>**0.028** | **-0.44**<br>**0.016** | **0.39**<br>**0.033** | 0.21<br>0.277 | -0.33<br>0.072 | - |

## 5.4 Discussion

To our knowledge, this if the first study that directly compared clinical and experimental neurocognitive tests in the same population of athletes with and without a history of self-reported concussions that have returned to full competition. We examined a sample of male and female varsity collegiate hockey players using two tests including, the ImPACT$^{TM}$ neurocognitive test and an experimental dual-task paradigm. Our results showed no differences on ImPACT$^{TM}$ composite scores between athletes with and without a prior history of concussion. However, athletes with a history of concussion had significantly reduced accuracy on the auditory tone discrimination task in the dual-task condition compared to athletes with no history of concussion.

Our findings suggest that concussions may produce long-term changes in allocating attentional resources while performing two tasks simultaneously; however, these neurocognitive changes are not evident on the standard clinical assessment, that is, the ImPACT™. Therefore, it appears that concussions can produce long-term impairments in executive functions, which may only be evident during higher demanding dual-task measures.

Past research has shown the ImPACT to be an effective neurocognitive test for evaluating the acute effects post-concussion (Broglio et al., 2007; Iverson et al., 2006a; Schatz et al., 2006); however, it has been shown that it is not significant to detect long-term deficits (Broglio et al., 2006; Iverson et al., 2006b; Maerlender et al., 2010). Some research has suggested that concussions do not produce long-term deficits in cognitive functioning because the injury causes a transient change in neural functioning that typically resolves within 5-10 days (Iverson et al., 2006a; McCrory et al., 2013). In contrast, our dual-task results are consistent with a body of literature showing long-term deficits in executive functions in athletes with a history of concussion compared to athletes with no history of reported concussion (Bernstein, 2002; Cicerone, 1996; Howell et al., 2013a; Martini et al., 2011). It is possible that the ImPACT is not sensitive to the long-term effects of concussions because these individuals have restored enough cognitive resources to perform each task. In contrast, dual-task paradigms may be more sensitive to these long-term effects because dual-tasking places a greater demand on cognitive resources which are comproised in people with a history of concussion. Even though no ImPACT composite scores were significantly impaired, there were associations between the ImPACT's Visual Memory, Visual Motor Speed and Reaction Time composites with the experimental auditory cost measure, thus, some overlapping mechanisms may be used to perform each task.

Therefore, more research will need to be conducted to understand the relationship between these outcome variables.

The majority of research that successfully discriminated participants with and without a history of concussion has evaluated executive functions using a divided attention paradigm (Bernstein, 2002; Cicerone, 1996; Howell et al., 2013a, 2013b; Martini et al., 2011). The rationale for exploring these tasks is that most activities, especially dynamic team sports, require simultaneously processing multiple sources of information while performing goal-directed movements (Register-Mihalik, Littleton, & Guskiewicz, 2013). However, after a diagnosed concussion, research has shown that the ability to allocate attentional resources to one or more tasks presented simultaneously is impaired in many of these individuals (Howell et al., 2013a, 2013b). Moreover, research examining the allocation of attentional resources using electroencephalography (EEG) has reported that the P3b amplitude at the Pz electrode represents the capacity to allocate attentional resources for information processing. Broglio, Pontifex, O'Conner, and Hillman (2009) reported that participants with a history of concussion show a suppressed P3b amplitude at the Pz electrode compared to healthy controls while performing a novelty oddball task that requires allocating attention to two simultaneously presented tasks, similar to a dual-task situation. Although odd-ball behavioural measures were not affected by concussion history, the suppression in P3b amplitude may suggest a decreased capacity to allocate attentional resources. These deficits in higher cognitive functions are not picked up by the current clinical tests.

Clinical neurocognitive measures that only test a single cognitive function may have a reduced power at discriminating previously concussed athletes from non-concussed athletes because concussed participants may benefit from a cognitive reserve. Cognitive reserve is a concept used to describe how individuals with higher education, regular participation in physical and mental exercises, and greater occupational achievements have a lower risk of age-related cognitive decline because these people develop an extensive neural network that increases neural efficiency and capacity to recruit additional brain areas (Harrison et al., 2015; Tucker & Stern, 2011). This concept has been used to account for the unreliable relationship between brain damage and its clinical effects (Stern, 2002). For instance, some individuals may be able to sustain a concussion and show no clinically detectable decline because their brain contain an extensive neural network that can compensate for the cognitive loss experienced post-concussion (Stern, 2002). The cognitive reserve hypothesis has been explored in other brain pathologies (i.e., stroke or Alzheimer's) (Jenkins, Fox, Rossor, Harvey, & Rossor, 2000, Tucker & Stern, 2011), as well as in athletes with a history of concussion (Broglio, Eckner, Paulson, & Kutcher, 2012; Guskiewicz et al., 2005). For example, Guskiewicz et al. (2005) studied 2552 retired NFL players aged 50 or older using self-report questionnaires, general health surveys, and a mild cognitive impairment test, with 1513 players having a history of at least one self-reported concussion. The findings showed a greater cognitive decline associated with memory loss in players with a history of concussion compared to healthy age and education matched controls. Furthermore, a larger number of reported concussions resulted in greater physician diagnosed mild cognitive impairments. Even though Guskiewicz et al (2005) results are influenced by self/family-report questionnaires, the findings provide some evidence of the cognitive decline associated with concussions because the previously concussed athletes had greater cognitive impairments compared to the athletes without a history of concussion. We hypothesize that our sample of athletes with a history of concussion have higher cognitive reserve acquired through education and regular participation in physical and mental tasks, thus, can maintain performance on less cognitively demanding tasks. However, when cognitive limits are stressed (i.e. dual-tasking), the persisting damage to neural networks from a concussive injury results in poorer performance. To improve our understanding of the association between cognitive reserve and concussions, future research should focus on evaluating individuals across their lifespan.

In conclusion, executive function tests stressing attentional resources appear to be more helpful in discriminating participants with and without a history of concussion compared to current clinical neurocognitive tests. It is possible that our sample of university athletes had enough cognitive resources to perform the ImPACT test; however, when performing a task requiring more cognitive resources, capacity limits were exceeded and performance was affected. Therefore, we must combine higher demanding tasks with current clinical evaluations to ensure that athletes are safe for competition.

## Section 6: Part Three

### 6.1 Introduction

The study of eye movements has become a valuable tool for investigating the cognitive processes of attention and working memory, and to gain insight into the effects of concussions. Research with neurologically intact humans and animals has shown a strong association between eye movements, attention and working memory (Awh, Vogel, & Oh, 2006; De Haan, Morgan, & Rorden, 2008; Hoffman, 1998; Theewus, Kramer, & Irwin, 2011; Theewus, Belopolsky, & Olivers, 2009; Zhao, Gersch, Shnitzer, Dosher, & Kowler, 2012). For instance, studies have shown a tight coupling between attention and eye movements as humans can attend to a peripheral location by moving their eyes (i.e., overt attention shift). On the other hand, eye movements can be dissociated from attention as humans can remain fixed and peripherally direct attention to a different location (covert attention shift) (De Haan et al, 2008; Hoffman, 1998; Zhao et al., 2012). However, recent studies have found that even covert shifts of attention are associated with small amplitude involuntary eye movements called microsaccades (Hoffman, 1998; Peterson, Kramer, & Irwin, 2004; Otero-Millan, Troncoso, Macknik, Serrano-Pedraza, & Martinez-Condo, 2008; Zhao et al., 2012). It has been proposed that attention is the mechanism involved in selecting information to be encoded into working memory (Awh et al., 2006; Theeuwes et al., 2011). Although eye movements are tightly linked with attentional processes, research investigating the role of eye movements in working memory has been equivocal. Some studies have shown that the oculomotor system is highly important for encoding spatial information into working memory (Ball, Pearson, & Smith, 2013; Pearson & Sahraie; Theewus et al., 2009). On the other hand, studies have shown that moving the eyes while encoding object spatial location can be disruptive to working memory because both processes use the same attentional mechanism (Smyth & Scholey, 1994). Recently, separate research studies have shown that eye movements, attention and working memory may be disrupted following a concussion. However, no research to our knowledge has investigated the effect of concussions on attention and working memory during the performance of a visuospatial memory task. Therefore, the goal of the present study is to gain insight into the deficits in attentional and working memory processes in athletes who suffered a concussion by measuring their gaze behavior during a complex spatial working memory task.

Eye movements have been used to investigate the encoding of visual spatial targets into working memory in recent research (Ball et al., 2013; Patt et al., 2015; Pearson & Sahraie, 2003). For example, Ball and colleagues (2013) measured the spatial span on a Corsi block test in 24 healthy participants under two monocular viewing conditions, which restricted eye movements to peripheral locations. Spatial span was defined as the largest target sequence correctly recalled during the Corsi test. Participants were either directly positioned in front a computer screen and remained fixated on a central cross or rotated 40 degrees and abducted their viewing eye toward a central fixation during the presentation of Corsi blocks. In both viewing conditions participants were instructed to maintain fixation and use covert attention to encode target locations. Results showed that Corsi span was significantly reduced in the abducted viewing condition in comparison to the central fixation condition. These findings suggest that spatial working memory is highly dependent on the oculomotor system because restricting the ability to make target directed eye movements impaired performance on this spatial memory task compared to the condition where participants were able to potentially perform eye movements during sequence presentation (Ball et al., 2013).

Other research has shown that executing eye movements while maintaining spatial information is disruptive to working memory performance (Lawrence, Myerson, & Abrams, 2004). For example, Lawrence et al (2004) studied 30 participants on a spatial working memory task requiring participants to remember a series of blue circles presented within a 20-cell matrix. A secondary task was used to disrupt the maintenance of spatial memory and required participants to discriminate between an X or + target appearing $6.45^{o}$ to the left or right of a central fixation. Participants were instructed to either remain fixed on the central fixation (covert attention) or move their eyes to the target (over attention) during the discrimination task. Results showed that executing eye movements during the discrimination task resulted in poorer performance on the spatial working memory task compared to the covert attention condition. These findings suggest that executing eye movements during maintenance of spatial information produces more interference than remaining fixed and covertly shifting attention. Therefore, the research suggests that the oculomotor system is needed for encoding visuospatial information into working memory (Ball et al., 2013); however, overt shifts in attention may interfere with the maintenance of spatial processing so covert shifts of attention are more helpful to remember target location (Lawrence et al., 2004).

More recent research by Patt et al (2015) has explored gaze strategies used by healthy participants to store spatial targets into working memory. Twenty-five healthy adults were tested on the Corsi block test during natural viewing. The findings showed that participants had a tendency to become more fixated on a central location when the Corsi block sequence increased in difficulty (i.e., more targets presented). The more fixated gaze strategy indicates a greater reliance on covert attention to encode target locations into working memory. During post-experiment interviews participants reported that they remained fixed and integrated information about the whole configuration rather than moving their eyes to every Corsi target to encode their locations separately (Patt et al., 2015). These findings suggest that executing eye movements to encode visuospatial targets can be disruptive to remembering spatial locations, thus, participants use a more fixated strategy (i.e., covert attention) to encode targets. However, little is still known about the gaze strategies used by participants with a history of brain injury (i.e., concussions) because these individuals may use different gaze strategies given they typically have persisting impairments in attention, working memory, and eye movements (Berstein, 2002; Howell et al., 2013; Heitger, Anderson, & Jones, 2002; Heitger et al., 2009; Kraus et al., 2007).

Recently, the examination of eye movements haas become a helpful tool for understanding the effects of concussions (Heitger et al., 2002; Heitger et al., 2009: Kraus et al., 2007; Vernau et al., 2015). For example, Heitger et al (2009) studied 72 participants (36 post-concussion syndrome -PCS) on 3 oculomotor tests including, reflexive saccades, antisaccades and memory-guided saccades. Reflexive saccades are defined as a saccade directed toward a stimulus and have been shown to be exogenously triggered by the parietal eye fields with execution controlled by the superior colliculus (Peirrot-Deseilligny, Muri, Nyffeler, & Milea, 2004). An antisaccade is defined as a saccade directed in the opposite direction of a stimulus, thus, a reflexive saccade must be inhibited and a voluntary movement must be made in the opposite direction. Inhibiting unwanted movements is a processes controlled by the dorsolateral prefrontal cortex (DLPFC) (Munoz & Everling, 2004). Memory-guided saccades are a reflection of spatial memory because participants are instructed to make an accurate saccade to a remembered target position, thus, individuals must inhibit unwanted movements and execute a saccade to the correct location, a process dependent on the activity in the frontal eye fields (FEF) and controlled by the DLPFC. Studies have shown that participants suffering from PCS had a significantly higher frequency of eye movements and a larger final eye position error during memory-guided sequences, and more directional errors during the antisaccade test compared to the healthy controls (Heitger, Jones,& Anderson, 2008; Heitger et al., 2009). In contrast, the two groups showed no differences on the reflexive saccade test. These findings suggest persisting impairments in DLPFC function because the DLPFC is responsible for controlling memory-guided saccades and inhibiting unwanted reflexive saccades (Peirrot-Deseilligny et al., 2004). Similar oculomotor findings were reported by Heitger et al (2004) in the acute concussion phase (i.e., within 10 days post-injury), who reported more directional errors during the memory-guided and antisaccade tests which indicates problems with accurately planning and execution of eye movements, and with inhibiting unwanted eye movements. These results provide insight into the oculomotor impairments that may affect visuospatial encoding in participants with a diagnosed concussion; however, no research has studied gaze strategies in participants with a history of concussion instructed to encode visuospatial target location.

Several research studies examining the long-term effects of concussions have shown persistent impairments in executive functions including, allocation of attentional resources and working memory (Bernstein, 2002; Howell et al., 2013; Heitger et al., 2009). For instance, Heitger et al (2009) reported that participants suffering from PCS had persisting deficits on neurocognitive tests requiring executive functions including, D-KEFS Colour-Word interference task (Stroop test) and the Trail-Making Test. These findings suggest problems in DLPFC function because the DLPFC plays an important role in executive functions such as working memory, inhibition, planning, and task-switching (Chan, Shum, Toulopoulou, & Chen, 2008). More recent research with participants who had a history of concussion but were symptom free and had returned to daily activities has shown chronic deficits on executive function tests requiring participants to allocate attentional resources while performing two tasks simultaneously (Bernstein, 2002; Howell et al., 2013). For example, Howell et al (2013) studied 20 participants using the Attentional Network Test and Task-Switching Test at 5 time points post-concussion (72h, 1wk, 2wks, 1-month, 2-months) and compared the results to 20 healthy control subjects. Results showed that the concussed group performed significantly worse on the Attentional Network Test and Task-Switching Test at all five time-points, as indicated by a slower reaction and greater switch cost, compared to healthy controls. Importantly, participants with a concussion reported being symptom free at the 2-week time point, however, they still suffered in performance on the tasks measuring executive functions. Therefore, research suggests that concussions produce long-term deficits to the cognitive processes and oculomotor mechanisms controlled by the DLPFC, which, in turn, may affect the encoding and recall of visuospatial information.

The present study examined the gaze strategies used by athletes with and without a history of concussion to encode visuospatial information into working memory. Furthermore, gaze behaviour was examined during task conditions with progressively greater cognitive demands (i.e., dual-tasking). Our main hypothesis was that athletes with a history of concussion will perform more eye movements per target because previous research has shown that these athletes have difficulty with inhibiting reflexive target-directed movements compared to athletes with no concussion history. Additionally, the rate of eye movements will increase in athletes with a history of concussion as the cognitive demands increase (i.e. task and level difficulty) because the increasing task demands will require attentional resources resulting in less available resources to inhibit reflexive movements. In contrast, athletes with no prior history of concussion will become more fixated as task and level difficulty increases.

## 6.2 Methods

### 6.2.1 Participants

Participants were the 29 varsity collegiate ice hockey players. Their demographic characteristics are described in sections 4 and 5.

### 6.2.2 Materials and Procedure

The detailed experimental protocol is described in sections 4 and 5. Briefly, participants were placed in an adjustable chin-rest located 80cm from the visual screen. Participants wore an Eyelink II eyetracker during the acquisition and recall phase of the Corsi block test in both experimental conditions (single, dual). The eyetracker was calibrated using a 9- point calibration grid presented on a 19 inch Viewsonic CRT monitor (resolution 1024x768, refresh rate 85 Hz). A validation procedure was used to ensure that both eyes were within one degree of error before the task began. Eye movements were recorded at 250 Hz using a pupil-only recording mode. Participants were instructed to fixate on a central fixation cross at the beginning of each trial, but during the trial they were free to move their eyes naturally.

### 6.2.3 Data Analysis

Eye movement analysis was completed using the SR Research Data Viewer software (version 1.0), MATLAB software package R2013b (The Mathworks Inc., Natick, MA, 2000) and Microsoft Excel (MS Office 2013). First, raw binary data files were exported from Eyelink II Data Viewer software and converted to an ASCII file. The ASCII files were imported into Microsoft Excel using the delimited option, and saved as an Excel workbook file. Eye position data were converted from pixels to degrees of visual angle for the horizontal and vertical axis using an 80cm viewing distance ($\sigma° = \text{atan}(\frac{object\ size}{Viewing\ Distance})$). The centre of the computer monitor was defined as coordinates (0, 0). Saccade upward or to the right of the central fixation were defined as positive in the vertical and horizontal axis, respectively. Saccades downward or to the left were defined as negative. Every trial was separated into an acquisition phase, defined as the period in which participants were presented with the targets to be remembered, and recall phase, defined as the period in which participants selected the targets that were presented in the acquisition phase. Since we only focused on the acquisition phase (i.e., encoding phase), the acquisition data were analysed further using a MATLAB script developed for detecting saccadic eye movements.

For our analysis, only Corsi levels 3-7 were included because level 2 was used as a practice trial so that participants could become familiar with the task, and level 8 did not have a sufficient sample size to conduct analyses. Saccades were detected using a velocity threshold criteria, using a peak velocity threshold set to >50 deg/s, while saccade initiation was determined when the eye exceeded velocity 20 deg/s. All eye position traces were inspected visually to confirm the saccades that were marked automatically using the MATLAB script. Saccade data from each trial were exported into an excel file which included saccade latency, amplitude, duration, peak velocity and gain. All data were screened for outliers by plotting the main sequence relationship (i.e., amplitude vs. peak velocity) for each participant. All outliers, defined as plus or minus 3 standard deviations from the regression line, were further inspected and removed from the main analysis.

The location of Corsi targets varied between 0.93 to 13.39 degrees from the central fixation cross. The following criteria were used to separate saccades into three categories: 1) task relevant saccades directed toward the target, which were defined as eye movements with amplitude >1.2$^{o}$ or gain >10%, 2) microsaccades, defined as saccade with amplitude <1.2$^{o}$ with a gain <10%, and 3) other saccades, defined as any saccade that was not directed toward the target with amplitude >1.2$^{o}$.

First, the total number of saccades in each category was recorded for each target during acquisition phase. Then, data were converted to a saccade rate per target by dividing the number of eye movements by the target time interval (i.e. 0.75s). The saccade rate was the dependent variable which represented the rate (Hz) of task-relevant saccades, microsaccades, and other saccades.

### 6.2.4 Statistical Analysis

The main hypothesis for this study was examined using the combined total rate of horizontal and vertical eye movements per target as the dependent variables for each of the three eye movement categories. The rate of horizontal (x) and vertical (y) saccades was also examined. Three separate 3-way mixed model ANOVA's were conducted to examine the difference in the rate of task relevant saccades, microsaccades, and other saccades. The between-subject factor was Concussion History (no concussion, concussion), the two within-subject factors were Task (single, dual), and Difficulty Level (3-7). Significant interactions within the 3-way model were investigated using a Tukey-Kramer post-hoc test.

Analysis was also conducted to examine the gain per target in the horizontal and vertical axis using a 3-way mixed model ANOVA. The between-subject factor was Concussion History, the two within-subject factors were Task and Difficulty Level.

### 6.2.5 Results

Our main hypothesis examined the rate of task relevant saccades using a 3-way ANOVA. Results showed a significant main effect for Difficulty Level (4, 108) = 14.31, $p < .001$, $d$ = 0.74. However, Concussion History was not significant (1, 27) = 2.45, $p$ = 0.1291, $d$ = 0.30 (see Figure 6.1). There were no significant interactions (see Figures 6.2 and 6.3). The analyses examining the rate of horizontal and vertical task relevant saccades using a 3-way ANOVA showed a significant main effect of Difficulty Level for both horizontal $F$ (4,108) = 14.31, $p <$ .001, and vertical saccades $F$ (4, 108) = 18.64, $p < .001$. Concussion History was not significant for horizontal saccades $F$ (1, 27) = 2.72, $p$ = 0.111, and vertical saccades $F$ (1, 27) = 2.35, $p$ = 0.137, as shown in Figure 6.4.

Figure 6.1

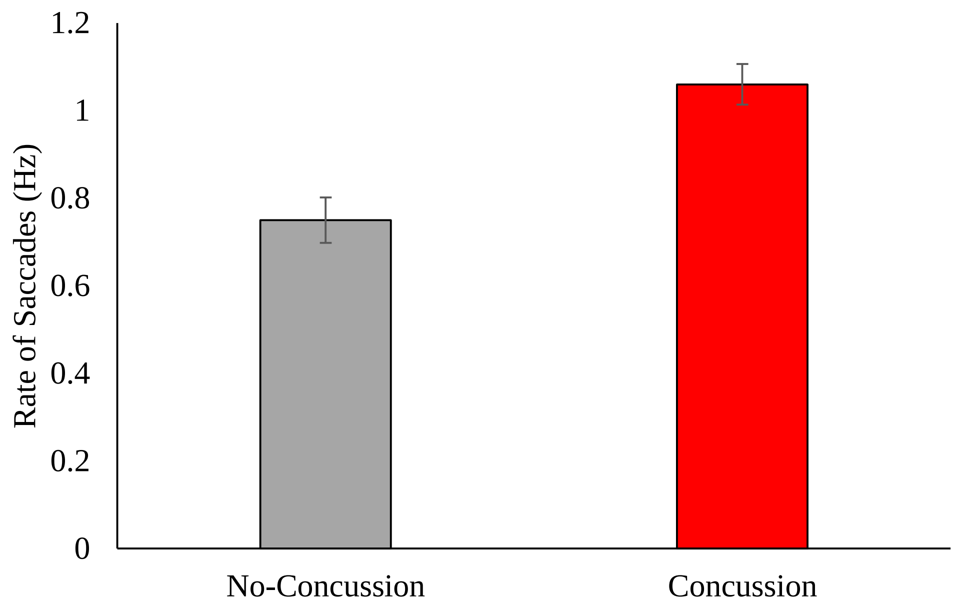


**Figure 6.1:** Rate of task relevant saccades per target separated by concussion history. The light grey bar represents participants with no history of concussion. The red bar represents previously concussed participants. No significant differences were shown between the two groups.

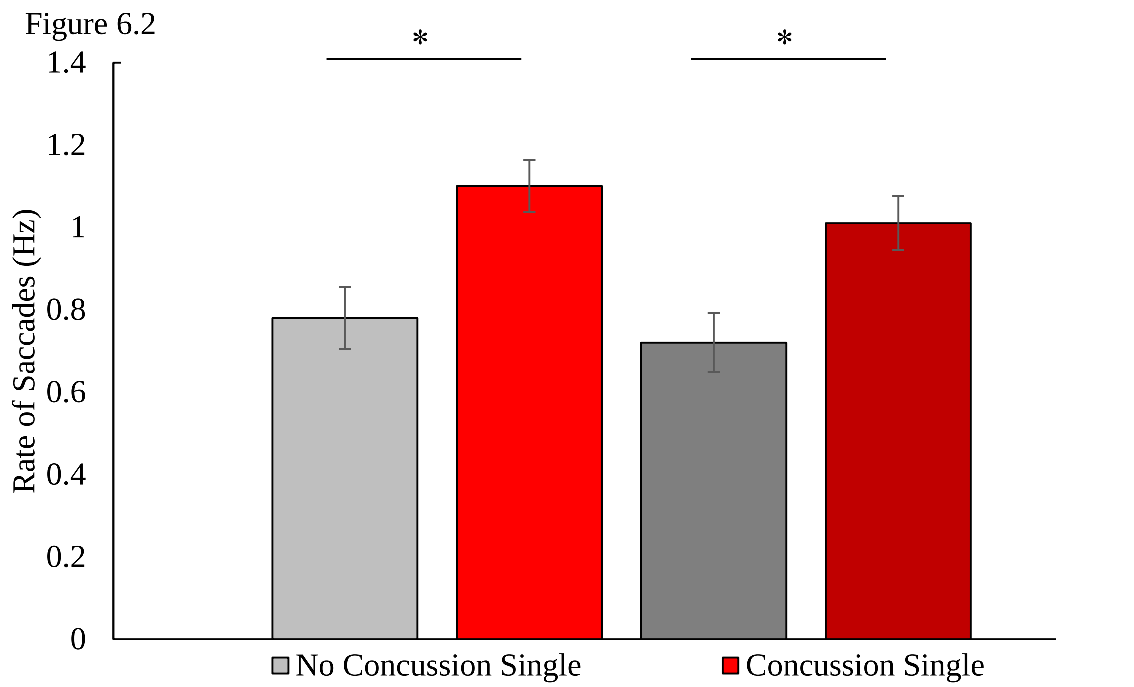


**Figure 6.2:** Rate of task-relevant saccades separated by Concussion History and Task. Significant differences were shown in both single and dual conditions.

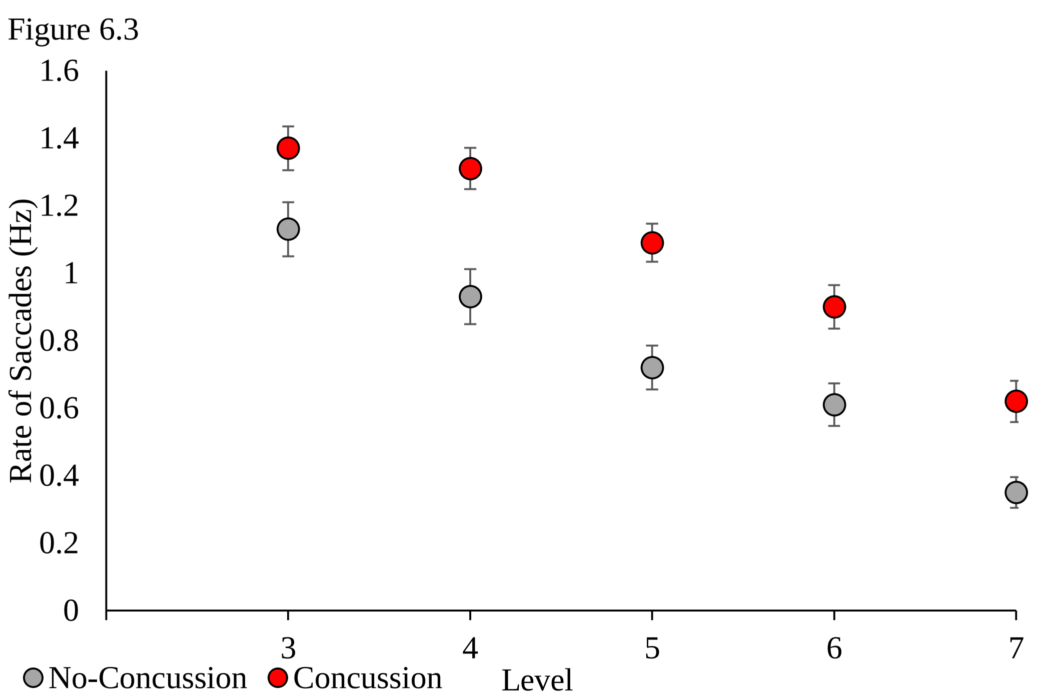


**Figure 6.3:** Rate of task-relevant saccades separated by Concussion History and Difficulty Level. Levels 4 and 5 are statistically different.

Figure 6.4

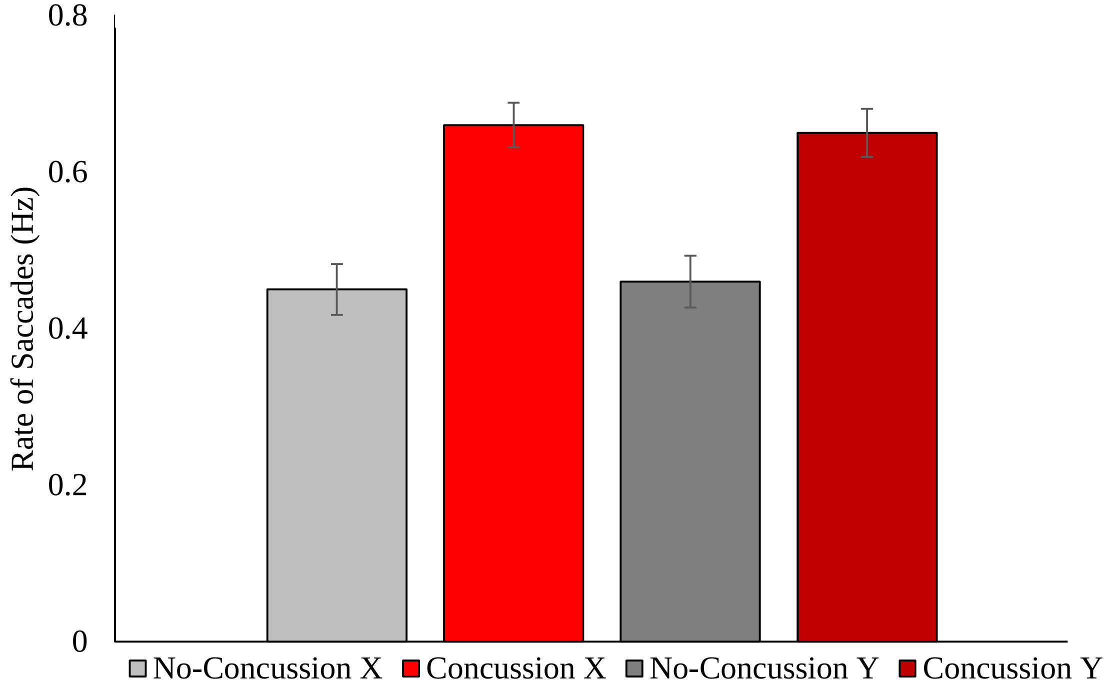


**Figure 6.4:** Rate of task-relevant saccades for horizontal saccades (X) and vertical saccades (Y) separated by Concussion History. Horizontal saccades are represented by light grey and light red bars. Vertical saccades are shown by dark grey and dark red bars.

Next, the rate of microsaccades was examined using a 3-way ANOVA. The ANOVA revealed a significant main effect of Difficulty Level $F$ (4, 108) = 7.25, $p$ < .001, $d$ = 0.82. There were no significant effects for Task or Concussion History and no significant interactions. The rate of microsaccades for each concussion history group are reported as follows: concussion (M = 0.22, SD = 0.32), no-concussion (M = 0.19, SD = 0.31) (see Table 6.1). Further analysis of horizontal and vertical microsaccades also showed a significant main effect of Difficulty Level $F$ (4, 108) = 5.77, $p$ < .001 and $F$ (4, 108) = 4.80, $p$ = 0.001, respectively. There were no significant effects for Task or Concussion History and no interactions.

**Table 6.1**: Saccade Category Effects

| Saccade Categories | Effects | *df* | F value | *p* | Partial eta squared ($n_p^2$) | Effect Size (*d*) | Power |
|---|---|---|---|---|---|---|---|
| **Task-Relevant Saccades** | | | | | | | |
| | Concussion History | 1 | 2.45 | 0.129 | 0.083 | 0.30 | 0.60 |
| **Microsaccades** | | | | | | | |
| | Concussion History | 1 | 0.50 | 0.486 | 0.018 | 0.14 | 0.17 |
| **Other Saccades** | | | | | | | |
| | Concussion History | 1 | 1.29 | 0.266 | 0.046 | 0.22 | 0.36 |
| **Horizontal Gain** | | | | | | | |
| | Concussion History | 1 | 2.56 | 0.121 | 0.086 | 0.31 | 0.61 |
| **Vertical Gain** | | | | | | | |
| | Concussion History | 1 | 1.73 | 0.199 | 0.060 | 0.25 | 0.46 |

The rate of other saccades was also tested with a 3-way ANOVA. The ANOVA revealed a significant main effect of Task $F$ (1, 27) = 6.39, $p$ = 0.018, $d$ = 0.49, and Difficulty Level $F$ (4, 108) = 13.27, $p$ < .001, $d$ = 0.70. There was no main effect of Concussion History $F$ (1, 27) = 1.29, $p$ = 0.266, d = 0.22 (see Table 6.1). Therefore, both groups made fewer eye movements in the dual-condition compared to the single-condition, and as the level increased from 3 to 7 (see Figure 6.5). Additionally, no significant interactions were found. The analysis of horizontal and vertical saccades showed a significant main effect of Difficulty Level for both horizontal saccades $F$ (4, 108) = 14.85, $p$ < .001, and vertical saccades $F$ (4, 108) = 4.09, $p$ = 0.004, and Task for vertical other saccades $F$ (1, 27) = 13.73, $p$ = 0.001.

Figure 6.5

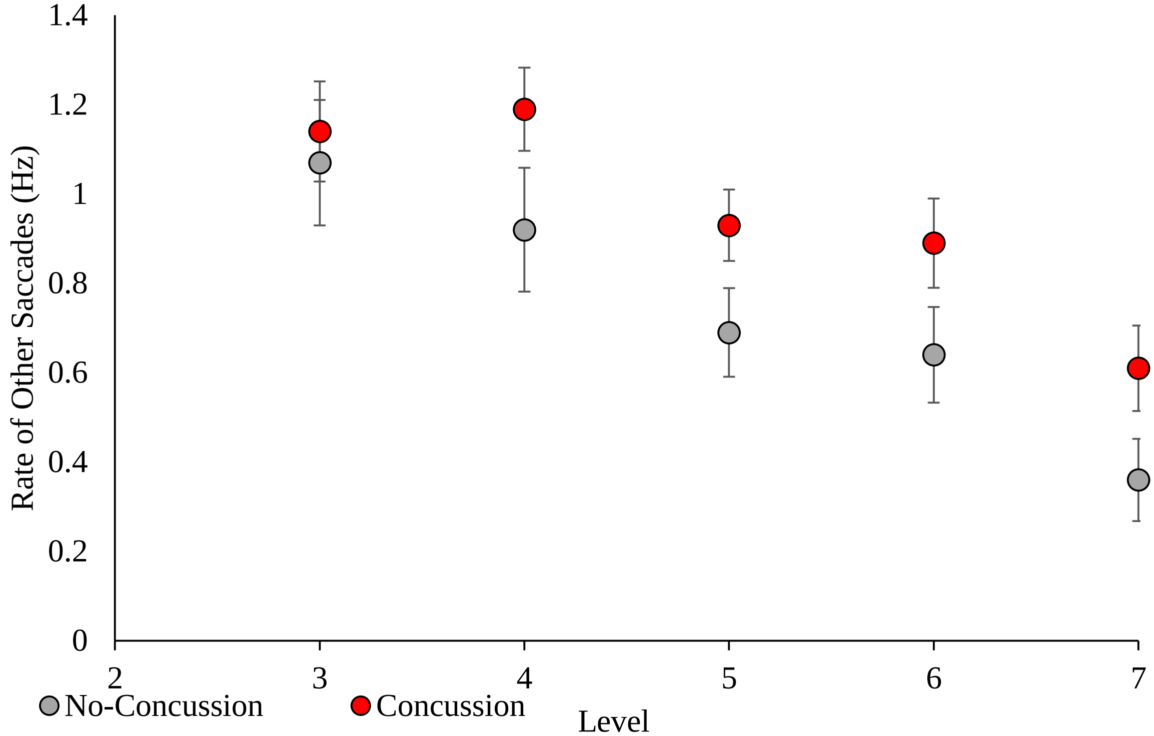


**Figure 6.5:** Rate of other saccades separated by Concussion History and Difficulty Level. Light grey dots represent no-concussion. Red dots represent participants with a history of concussion. There was a significant difference between groups at level 4.

Additional analysis of our main hypothesis examined the horizontal and vertical saccade gain using a 3-way ANOVA. A significant main effect of Difficulty Level was shown for both horizontal gain $F$ (4, 108) = 13.62, $p$ < 0.001, and vertical gain $F$ (4, 108) = 13.75, $p$ < 0.001. Gain was not significantly different between athletes with and without a concussion history for either horizontal $F$ (1, 27) = 2.56, $p$ = 0.121, $d$ = 0.31, or vertical gain $F$ (1, 27) = 1.73, $p$ = 0.199, $d$ = 0.25 (see Figure 6.6). No significant interactions were found (see Figure 6.7 & 6.8).

Figure 6.6

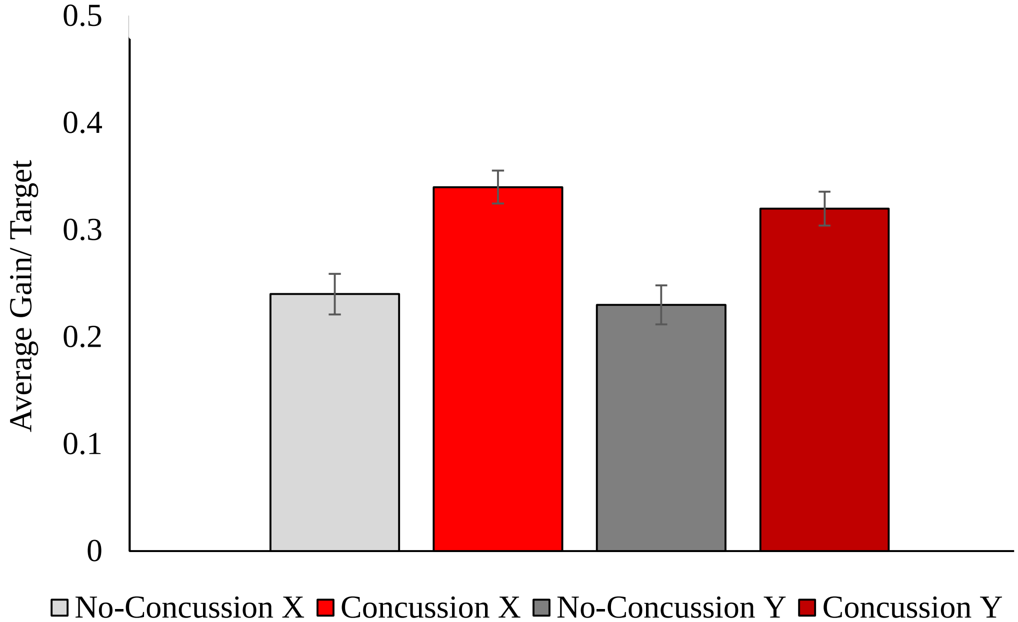


**Figure 6.6:** Average gain per target in both the horizontal (X) and vertical (Y) axis. Grey bars represent non-concussion participants. Red bars show previously concussed participants.

Figure 6.7

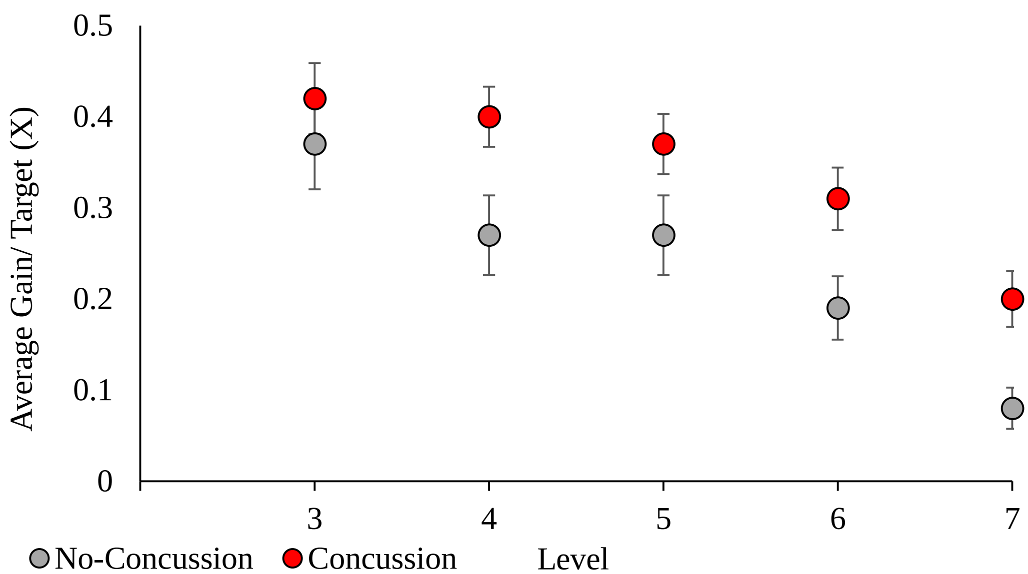


**Figure 6.7:** Average gain per target by Difficulty Level for horizontal saccades (X). Grey dots (non-concussed) and red dots (concussion). Significant differences were shown at levels 4-7.

Figure 6.8

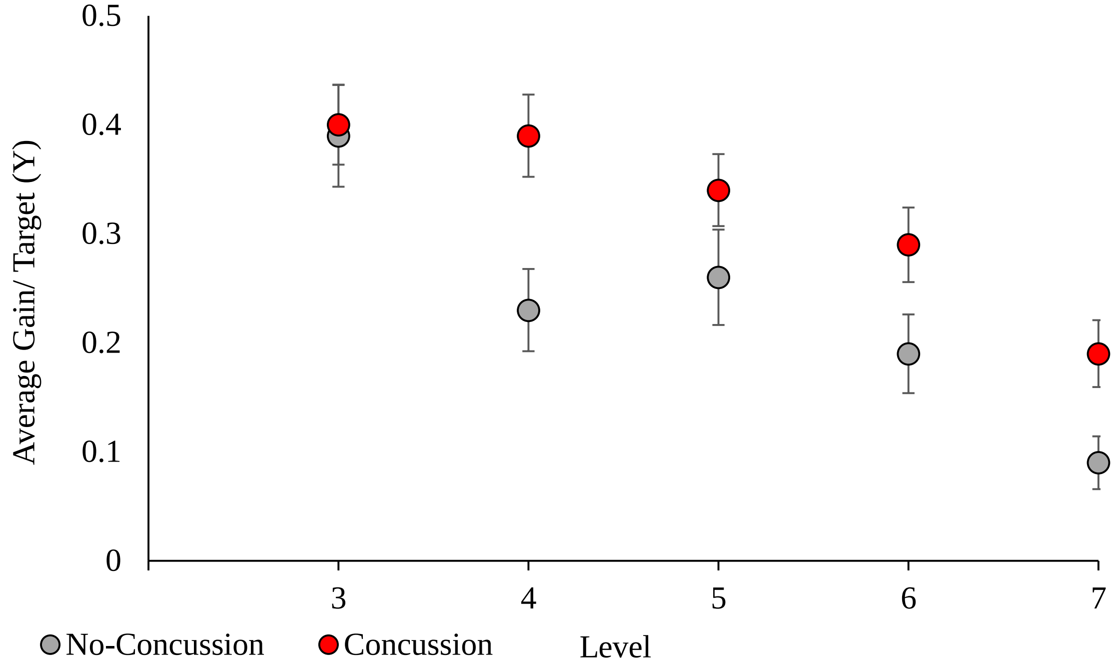


**Figure 6.8:** Average gain per target by Difficulty Level for vertical saccades (Y). Grey dots (non-concussed) and red dots (concussion). A significant difference was shown at level 4.

### 6.2.6 Discussion

To our knowledge, the present study is the first investigation that has characterized natural gaze strategies used by athletes with and without a history of concussion while encoding visuospatial information into working memory. Furthermore, we investigated the encoding strategies using different tasks that place a progressively greater demand on cognitive resources (i.e., increasing number of targets and a dual-task condition). The findings showed that all athletes, regardless of concussion history, decreased their rate of task-relevant saccades and other saccades as the difficulty level increased. However, there appears to be a trend showing that participants with a history of concussion had a higher rate of saccades and a higher gain of task relevant saccades compared to the non-concussed participants. In contrast, athletes without a history of concussion had a lower rate of saccades with smaller gains to each target presented suggesting a preference for a more fixed gaze strategy to encode Corsi targets. These results indicate that participants with a history of concussion perform more overt shifts of attention compared to non-concussed participants. Although the statistical significance for each saccade category shows insignificant differences, the effect sizes provide valuable information about the study.

Statistical significance (*p*) is a valuable measurement used to determine the probability of difference between two study groups (Sullivan & Feinn, 2012). Furthermore, statistical significance is largely influenced by the study's sample size which can lead to the over reporting of trivial effects and under reporting of actual and important effects. Even though statistical significance is helpful to find differences between groups, it lacks a critical description of the magnitude of difference between the two groups. To gain more knowledge into this, substantive significance (effect size) is often used to determine the practical and theoretical value of an effect (Fritz, Morris, & Richler, 2012). Effect size is a quantitative measure that reports the magnitude of difference between study populations and it has been highly recommended to report and interpret the effect size in behavioural sciences (Cohen, 2013). Although our study was underpowered to detect a statistically significant effect for the rate of saccades between the two concussion history groups, the effect size that was found is considered medium and behaviourally important (Fritz et al., 2012; Sullivan & Feinn, 2012, Cohen 2013). For that reason, we will focus on the effect size significance as opposed to statistical significance.

The present study showed a medium effect size for the three main outcome measures including, task-relevant saccades, horizontal saccade gain, and vertical saccade gain. Despite the lack of statistical significance, these are important findings which indicate that athletes with a history of concussion perform more eye movements during encoding of visuospatial targets. An interpretation for these results are that athletes with a history of concussion have less available attentional resources to inhibit irrelevant saccades as cognitive demands increase, thus causing deficits in spatial processing of auditory tones. In contrast, the non-concussion group performed fewer eye movements as difficulty level increased which may be a more beneficial strategy for extracting task-relevant information from their environment (Mann, Williams, Ward & Janelle, 2007; Hoffman, 1998). For example, research has shown (Mann et al., 2007) that expert athletes perform fewer fixations to process and perceive their immediate environment. However, concussions may affect these gaze strategies, thus, these individuals are unable to process task-relevant information that is valuable to performing goal-directed movements when cognitive demands increase.

Recent research has shown that healthy participants naturally prefer to remain fixed on a central target when encoding a series of sequentially presented peripheral targets (Patt et al., 2015). Similar to Patt el al (2015), our sample of non-concussed participants remained more fixed on the central fixation cross as the Corsi block sequence increased in difficulty (i.e., more targets presented). In addition, our sample of previously concussed participants followed a similar trend becoming more fixed on the central fixation as difficulty level increased. However, the rate of eye movements in athletes with a history of concussion was greater compared to the no-concussion group. This outcome suggests that both our groups relied more on covert attention to encode spatial targets into working memory as opposed to overtly moving their eyes to each target. A possible rationale for using this strategy is that overt shifts of attention can create a greater interference during visuospatial processing compared to covert shifts of attention. Specifically, visuospatial processing may be disrupted because attentional resources are engaged in performing the saccade (Irwin & Brockmole, 2000). The process of directing attention to behaviourally relevant information and inhibiting other behaviours is controlled by the DLPFC (Pierrot-Deseilligny et al., 2004) which may suggest that the previously concussed athletes may have a general disruption to the neural networks related to DLPFC functioning. Therefore, they cannot allocate the attentional resources to inhibit unwanted movements because their capacity limits have been reached (Heitger et al., 2002; Heitger et al., 2009; Kraus et al., 2007).

Past research examining oculomotor function and neuropsychological test performance in participants with and without a history of concussion has shown persisting deficits in oculomotor function and neuropsychological tasks requiring executive control (Heitger et al., 2009; Kraus et al., 2007). For example, Kraus et al (2007) tested 56 participants on two oculomotor tests (reflexive, antisaccades) and a neuropsychological test battery evaluating executive functions including, attention and memory (e.g., Stroop Test, Trail Making Test, Paced Auditory Serial Addition Test). Twenty participants had a history of mild traumatic brain injury (mTBI), and 17 had a history of severe traumatic brain injury (sTBI) acquired through sports-related injuries, falls, and motor vehicle accidents. The findings showed that participants with a history of mTBI and sTBI had more errors on the ant-saccade test which correlated with poorer performance on tasks assessing executive functions compared to healthy controls. The increased errors on the anti-saccade test indicated a greater difficulty inhibiting reflexive movements. Also, worse performance on the neuropsychological tests assessing executive functions reflects persisting impairments in DLPFC functioning (Howell et al., 2013; Kraus et al., 2007). Similar to previous findings, we showed that participants with a history of concussion that have returned-to-play perform more eye movements when encoding visuospatial targets which may result from a persisting disruption to prefrontal functioning. Additionally, our sample of previously concussed participants performed worse on a dual-task paradigm assessing executive functions (see Section

1). Therefore, it appears that concussions can cause subtle long-term impairments in prefrontal functioning which may reflect the different encoding strategies used between the two groups (concussion, no concussion) in our sample.

In conclusion, eye movements provide valuable information on where attentional resources are being allocated. They help us develop an understanding of how humans perceive and process their environment during tasks requiring different cognitive demands. Based on our findings, concussions appear to produce long-lasting deficits to attentional mechanisms which can affect the available resources required for humans to process their environment. Importantly, athletes that compete in cognitively demanding environments require large attentional resources (i.e., contact sports) to perform effectively. However, if concussions cause long-lasting impairments to attentional resources, then these individuals will have a harder time processing information in a fast-paced environment and, as a result, will place themselves at risk for further injury. Therefore, results from this study have important implications for improving current return-to-play guidelines, designing more sensitive tests, and developing both physically and cognitively demanding training programs to ensure athletes return to play safely.

## Section 7

### 7.1 General Discussion

Concussions have become a serious concern in sports and recreation due to significant long-term and chronic impairments in executive functions (Bernstein, 2002; Howell et al., 2013) and oculmotor control (Heitger et al., 2009; Kraus et al., 2007). Currently, clinical neurocognitive tests do not evaluate executive functions or oculomotor control and fail to discriminate athletes with and without a history of concussion in the long-term (Broglio et al., 2006; Iverson et al., 2006; Maerlender et al., 2010). However, many contact sports require executive functions to allocate attentional resources to multiple sensory inputs within the environment which are then used to guide goal-directed movements. Multiple sensory inputs are used to plan and execute goal-directed behaviours; however, visual and auditory inputs play an important role in locating teammates, objects, and the opposition in contact sports. Therefore, visuospatial and auditory processing tasks can provide valuable information on how athletes with and without a history of concussion process their environment.

The present research provides insight into the long-term effects of concussions on the cognitive processes responsible for information processing, that is, attention and working memory. Furthermore, our research has created new knowledge on the eye movement strategies used to encode information into working memory. As shown, encoding strategies were different between athletes with and without a history of concussion, which may describe some persisting underlying neurological impairments that occur in athletes with a previous concussion. Importantly, concussions can cause persisting impairments in cognitive processes responsible for information processing. Moreover, these athletes are participating in fast-paced environments that require excellent cognitive processing abilities to perform. However, if long-term impairments affect their cognitive abilities, then these athletes could be placing themselves in situations that increase their risk for further injury. Therefore, current guidelines need to be improved to ensure athletes are both physically and cognitively ready for competition.

### 7.2 Implications and Limitations

There are some implications of this research that can be used for future studies. First, our results on the long-term effects of concussions provide evidence for the development of a more sensitive test to diagnose and track recovery. Currently, return-to-play guidelines typically follow a stepwise progression beginning with being symptom free during no activity and increasing up to full contact practice; however, cognitive guidelines are less demanding. Therefore, return-to-play guidelines should include both a progressive increase in physically demanding tasks, and separate cognitively demanding tasks to ensure athletes are ready to competition Secondly, our research may be used to identify individuals that have suffered a previous concussion, or experience problems allocating attention. This would be valuable considering many athletes do not have baseline concussion measures, thus, it would helpful in recognizing those at a higher risk for injury. Finally, our research can be explored in other areas outside of concussions including, Alzheimer's, dementia or other brain dysfunction diseases. Since these diseases are often characterised by frontal lobe dysfunction, our test for executive functions may be a helpful screening tool to recognize early cognitive impairments.

This research does have some limitations that should be addressed in future research. First, we did not have a large enough sample size of non-concussed male athletes (n=4), thus, a more accurate comparison between sex may provide better insight into the effects of concussions because there has been different hypothesis on the recovery process between males and females. Second, we should have administered the Corsi block test alone a second time to test for reliability of the Corsi span. Similar to the tone discrimination task, we should have had two single performance measures of Corsi memory span. Finally, we do not know if the underlying problems in executive functions played a role in our participants having a previous concussion, or if concussions caused executive function impairments, thus, a longitudinal design comparing baseline measures to different post-concussion time periods will be more helpful in disentangling this problem. However, longitudinal studies are both timely and costly, and out of the scope of this thesis project.

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Appendices

Appendix A

Table A1: Raw data scores

Corsi scores are based on the number of trials recalled (Max = 14). Auditory accuracy was calculated on a scale from 0.0 – 1.0. Both Corsi cost and Auditory cost were calculated using a dual-task equation with negative (-) values indicating poorer performance in the dual-condition compared to the single-condition.

| Subject | Age | Gender | Number of Concussions | Time Since Last Concussion | Corsi Single (# of trials) | Corsi Dual (# of trials) | Corsi Cost | Auditory Accuracy Single | Auditory Accuracy Dual | Auditory Cost |
|---|---|---|---|---|---|---|---|---|---|---|
| 122100 | 23 | M | 1 | 76 | 6 | 2 | -0.67 | 0.87 | 0.44 | -0.49 |
| 122102 | 21 | M | 1 | 15 | 6 | 6 | 0.00 | 0.9 | 0.87 | -0.03 |
| 122104 | 24 | M | 3 | 2 | 8 | 6 | -0.25 | 0.83 | 0.64 | -0.23 |
| 122106 | 22 | M | 0 | 0 | 9 | 6 | -0.33 | 0.8 | 0.66 | -0.18 |
| 122107 | 23 | M | 1 | 98 | 8 | 7 | -0.13 | 0.87 | 0.68 | -0.22 |
| 122110 | 26 | M | 1 | 2 | 8 | 9 | 0.13 | 0.76 | 0.61 | -0.19 |
| 122113 | 23 | M | 1 | 51 | 10 | 7 | -0.30 | 0.95 | 0.57 | -0.40 |
| 122120 | 22 | M | 1 | 13 | 10 | 7 | -0.30 | 0.87 | 0.62 | -0.29 |
| 122127 | 23 | M | 0 | 0 | 4 | 3 | -0.25 | 0.68 | 0.6 | -0.12 |
| 122134 | 22 | M | 1 | 65 | 6 | 10 | 0.67 | 0.97 | 0.75 | -0.23 |
| 122135 | 23 | M | 3 | 24 | 8 | 3 | -0.63 | 0.52 | 0.3 | -0.42 |
| 122137 | 21 | M | 0 | 0 | 5 | 8 | 0.60 | 0.82 | 0.72 | -0.12 |
| 122138 | 23 | M | 1 | 24 | 5 | 5 | 0.00 | 0.98 | 0.61 | -0.38 |
| N1359 | 23 | M | 0 | 0 | 13 | 9 | -0.31 | 0.93 | 0.85 | -0.09 |
| 133100 | 19 | F | 2 | 12 | 6 | 9 | 0.50 | 0.83 | 0.69 | -0.17 |
| 133102 | 21 | F | 2 | 77 | 8 | 8 | 0.00 | 0.88 | 0.68 | -0.23 |
| 133107 | 19 | F | 0 | 0 | 4 | 7 | 0.75 | 0.98 | 0.8 | -0.18 |
| 133108 | 20 | F | 2 | NA | 7 | 6 | -0.14 | 0.97 | 0.61 | -0.37 |
| 133115 | 17 | F | 2 | 44 | 6 | 5 | -0.17 | 0.85 | 0.4 | -0.53 |
| 133116 | 21 | F | 0 | 0 | 6 | 6 | 0.00 | 0.85 | 0.86 | 0.01 |
| 133127 | 20 | F | 2 | 13 | 8 | 7 | -0.13 | 0.91 | 0.68 | -0.25 |
| 133130 | 19 | F | 2 | 12 | 5 | 7 | 0.40 | 0.94 | 0.69 | -0.27 |
| 133132 | 19 | F | 0 | 0 | 9 | 9 | 0.00 | 0.97 | 0.84 | -0.13 |
| 133141 | 19 | F | 2 | 33 | 6 | 5 | -0.17 | 0.92 | 0.73 | -0.21 |
| 133142 | 17 | F | 0 | 0 | 8 | 6 | -0.25 | 0.92 | 0.78 | -0.15 |
| 133151 | 18 | F | 0 | 0 | 8 | 7 | -0.13 | 0.94 | 0.88 | -0.06 |
| 133158 | 19 | F | 0 | 0 | 6 | 5 | -0.17 | 0.88 | 0.77 | -0.13 |
| 133169 | 18 | F | 0 | 0 | 7 | 8 | 0.14 | 0.92 | 0.82 | -0.11 |
| 133187 | 21 | F | 1 | 10 | 9 | 8 | -0.11 | 0.95 | 0.76 | -0.20 |

Appendix B

In-depth description of the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT)

The ImPACT test is a computerized neurocognitive test that takes 25-35 minutes to perform. The University of Waterloo administers the ImPACT test to all athletes that are at a high risk for concussion (i.e., contact-sports). The ImPACT baseline test is administered to athletes every two years by an athletic trainer, team doctor or professional psychologist. If a concussion is suspected during participation, the baseline serves as a comparison to post-injury ImPACT performance. A professional psychologist assess changes that are presented between the two testing reports to assist with diagnosis and return-to-play decisions.

The ImPACT test consists of six multi-dimensional modules assessing attention, working memory, sustained and selective attention, response variability, non-verbal problem solving and reaction time, and a 22-symptoms checklist ranging from minor (1) to severe (6) to quantify the severity of symptoms. The six modules include, Word Memory, Design Memory, X’s and O’s, Symbol Match, Colour Match (i.e. Stroop Test), and Three Letter Recall. Each of the six modules performed are used to calculate five composite scores that assist with concussion diagnosis and return-to-play decisions. The five ImPACT composite score include, Verbal Memory, Visual Memory, Visual Motor Speed, Reaction Time and Impulse Control.

**ImPACT Modules**

***Word Memory:*** Assesses attentional processes and verbal recognition memory. Subjects are individually shown 12 target words presented every 750ms twice in a row. Recall testing is performed using a list of 24 words that are comprised of the 12 target words and 12 non-target words (e.g. “ice” is a target word, “snow” is a non-target word). The subjects respond by clicking “yes” or “no” with a computer mouse.

***Design Memory:*** Assesses attentional processes and visual recognition memory. Subjects are presented with 12 target designs every 750ms (repeated twice). Then, subjects are tested with 12 target and 12 non-target designs and must accurately discriminate the correct design. Subjects respond with a “yes” or “no” using a computer mouse.

***X’s and O’s:*** Evaluates visual working memory and visual motor speed. Subjects are shown an array of X’s and O’s for 1.5 seconds with 3 X’s or O’s illuminated. Immediately after this presentation, a distractor choice reaction time test is shown to interfere with memory rehearsal. The X’s and O’s re-appears and subjects are asked to click on the previously highlighted X’s and O’s.

***Symbol Match:*** Measures visual processing speed, learning and memory. Subjects are shown 9 common symbols (ex. Triangle, square) each with a number button labelled 1 to 9 positioned underneath. One of the 9 symbols is presented below the horizontal grip and subjects are instructed to respond as quickly as possible by clicking the number corresponding with the symbol. After 27 trials, the symbols are removed from the top grid and subjects must perform the task by clicking the appropriate number button.

***Colour Match:*** Measures choice reaction time and response inhibition. Subjects are first assessed for colour blindness by responding to the colour word highlighted in the word colour (e.g. “Red” highlighted in red). Testing begins with a word displayed on the screen in the same colour (e.g. RED) or different colour then the word presented (e.g. BLUE). Subjects are instructed to click as quickly as possible when the word matches the colour.

***Three Letter Recall:*** Assesses working memory and visual-motor response speed. Subjects are presented with three letters. Then, subjects perform a distractor task that involves clicking 25 numbered buttons presented on a 5x5 grid in reverse order (e.g. 25-24-23 etc.). After 18 seconds, the distractor task disappears and subjects are instructed to type the three letters using the keyboard.

**ImPACT Composites**

The ***Verbal Memory*** composite is composed of the word memory, symbol match and three letter modules. The ***Visual Memory*** composite includes the design memory module and X's and O's module. The ***Visual Motor Speed*** composite is comprised of an interference task in the X's and O's module, and a countdown number task incorporated in the three letter memory module. The ***Reaction Time*** composite represents the average correct reaction time of the interference task during the X's and O's module, the average correct reaction time of symbol match module, and the average correct reaction time for the colour match module. The ***Impulse Control*** composite is obtained by adding the incorrect answers for the interference task of X's and O's, and incorrect answers for the colour/word match (i.e., Stroop task). The Impulse Control composite is used to identify participants that are perform poorly to set a low-baseline that will be easily achievable following a concussion. The term "sandbagging" is often used to characterize participants that perform poorly. If "sandbagging" is reported, participants are asked if they had any difficulties completing the test. If so, they will be retested.