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Executive function deficits in team sport athletes with a history of concussion revealed by a visual-auditory dual task paradigm

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ABSTRACT

The purpose of this study was to examine executive functions in team sport athletes with and without a history of concussion. Executive functions comprise many cognitive processes including, working memory, attention and multi-tasking. Past research has shown that concussions cause difficulties in vestibular-visual and vestibular-auditory dual-tasking, however, visual-auditory tasks have been examined rarely. Twenty-nine intercollegiate varsity ice hockey athletes (age = 19.13, SD = 1.56; 15 females) performed an experimental dual-task paradigm that required simultaneously processing visual and auditory information. A brief interview, event description and self-report questionnaires were used to assign participants to each group (concussion, no-concussion). Eighteen athletes had a history of concussion and 11 had no concussion history. The two tests involved visuospatial working memory (i.e., Corsi block test) and auditory tone discrimination. Participants completed both tasks individually, then simultaneously. Two outcome variables were measured, Corsi block memory span and auditory tone discrimination accuracy. No differences were shown when each task was performed alone; however, athletes with a history of concussion had a significantly worse performance on the tone discrimination task in the dual-task condition. In conclusion, long-term deficits in executive functions were associated with a prior history of concussion when cognitive resources were stressed. Evaluations of executive functions and divided attention appear to be helpful in discriminating participants with and without a history concussion.

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KEYWORDS
Concussions; athletes; mild traumatic brain injury; dividing attention

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), subacute (weeks) (Broglio, Macciocchi & Ferrara, 2007; Iverson, Gaetz, Lovell & Collins, 2004; McClincy, Lovell, Pardini, Collins & Spore, 2006) and long-term (months to years) (Bernstein, 2002; Cossette, Ouellet & McFadyen, 2014; Fait, Swaine, Cantin, Leblond & McFadyen, 2013; Howell, Osternig, van Donkelaar, Mayr & Chou, 2013) 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). A variety of impairments have been reported in the acute stage, including memory loss (Schatz, Pardini, Lovell, Collins & Podell, 2006), difficulties with orienting and dividing attention (Halterman et al., 2006; Howell et al., 2013), decreased processing speed (Schatz et al., 2006), changes in balance control or gait patterns (Catena, van Donkelaar & Chou, 2007), 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; Cossette et al., 2014; Fait et al., 2013; 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; 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 organising and executing goal-directed behaviours (Anderson, Jacobs & Anderson, 2011), such as planning and completing tasks that require attention, working memory and inhibition of prepotent responses (Chan, Shum, Toulopoulou & Chen, 2008; Friedman et al., 2008; Petersen & 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

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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 et al., 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; Kleffelgaard, Roe, Soberg & Bergland, 2012; Martini et al., 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 1 and 16 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 history of 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 are associated with a history of concussion.

Currently, our understanding of the effects of concussions in athletes is incomplete. Past research examining participants 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). 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 sample of university ice hockey players with similar sport-specific training. Our sample 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 the task that was not instructed to be prioritised (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 hypothesised that no differences would appear on the Corsi block test performance between concussion history or task condition because this was instructed to be prioritised.

Methods

Participants

Twenty-nine intercollegiate varsity ice hockey players were recruited from two teams (15 females, age = 19.1 ± 1.26 years old; 14 males, age = 22.25 ± 0.9 years old). All participants completed two separate health history questionnaires on different dates to assess reliability of self-reported concussion history and symptoms. The first questionnaire was the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT) health history questionnaire (Lovell, 2011). The second questionnaire was the University of Waterloo health history questionnaire (refer to Appendix) that asked questions regarding history of sports-related 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). An earlier version of the Waterloo Health History Questionnaire was used in a previous study (Locklin, Bunn, Roy & Danckert, 2010). 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. Participants were categorised into a concussion and non-concussion group based on a brief interview involving questions concerning a previous physician diagnosis, a description of the head injury event, and responses to the health history questionnaires. Participants were assigned to the group with a history of concussion if they met one of the three following criteria, (1) a previous physician diagnosed concussion; (2) a recorded concussion in the ImPACT database that included baseline and post-injury evaluations; or, (3) experienced the following symptoms lasting a minimum 4–7 days after being hit in the head in sports:

Table 1. Participant characteristics.

Health history	Gender	*n*	Age (M ± SD)	Years of sport played	Number of concussions	Time since injury (mos.)	Symptom checklist score (max = 132)
No-concussion	Female	7	18.7 ± 1.2	13.4 ± 1.2	-	-	3.2 ± 3.5
Concussion	Female	8	19.5 ± 1.3	12.4 ± 2.5	1–3	28.7 ± 24.9	1.5 ± 1.7
No-concussion	Male	4	22.2 ± 0.9	17.7 ± 0.9	-	-	2.0 ± 1.7
Concussion	Male	10	22.9 ± 1.4	17.7 ± 1.8	1–2	24.9 ± 33.4	1.4 ± 1.5

confusion, headaches, nausea, dizziness, blurred vision, memory loss, and balance problems. Eighteen athletes reported that they were diagnosed with at least one concussion resulting from contact while participating in ice hockey, and assigned to the concussion group (see Table 1). 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, seven athletes with two previous concussions and two athletes with three previous concussions. Eleven athletes reported no previous physician diagnosed concussion, had no record of injury in the ImPACT database, and had never experienced any of the previously stated symptoms after being hit in the head. As a result, 11 athletes were assigned to the non-concussion group. The unbalanced design occurred from recruitment procedures using only two ice hockey teams. Varsity ice hockey athletes with no history of concussion were unavailable and difficult to find at the varsity level. The study's protocol was approved by the Research Ethics Board Committee and all protocols adhered to the guidelines of the Declaration of Helsinki. Informed consent was obtained from each participant.

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 min 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 stabilised in a chinrest located 80 cm 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 computerised using E-prime software (v1.2) and presented on a computer monitor (visual single). As illustrated in Figure 1(a), the visual stimuli (i.e., Corsi blocks) were eight blue squares (8 mm × 8 mm) 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 750 ms 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 colour 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 colour. The first level began with a sequence of two targets (i.e., two blocks changed colour), 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 1(b)). 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.

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. Using the second tone discrimination task (auditory-single2) ensured that the total number of tones presented in the single and dual-task conditions were equivalent. Also, a second tone discrimination task condition was performed to assess practice effects.

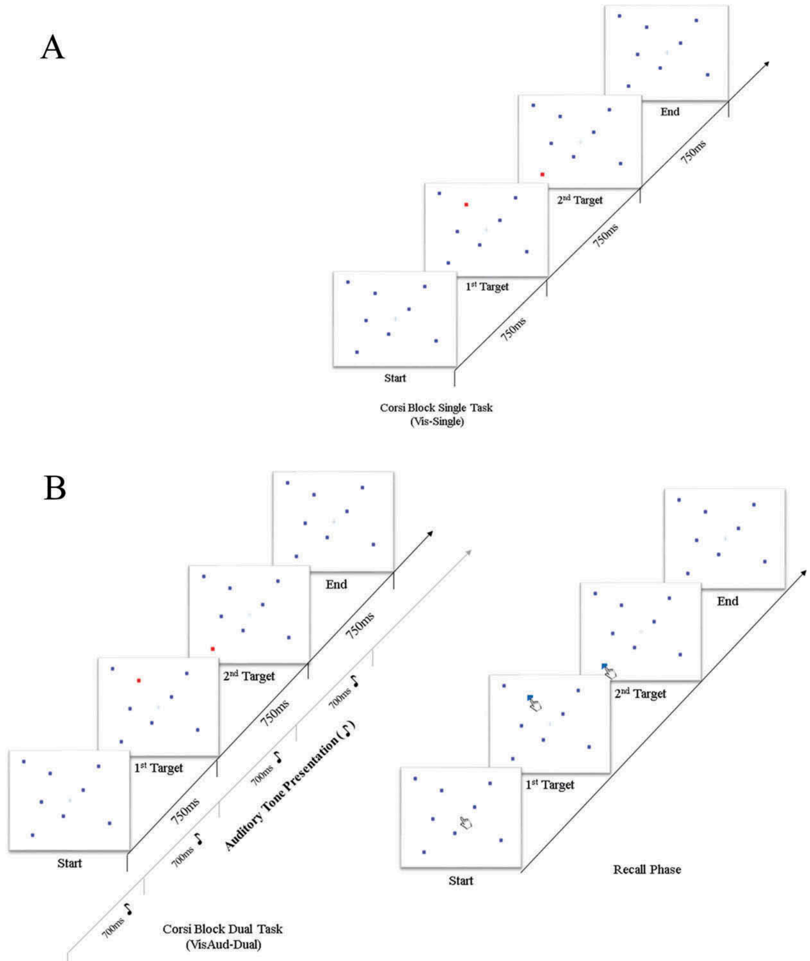

Figure 1. (a) Schematic diagram illustrating the Corsi block test sequence of events in the single-task condition (A [Vis-Single]) and the dual-task condition (B [Vis-Aud Dual]). Each trial began with a presentation of all blocks. During the acquisition phase, a sequence of blocks was highlighted, one block at a time for 750 ms.

The experimental design required participants to use their right and left hand to respond to two separate tasks. The left hand was used to click on a mouse during the tone discrimination task performed during the acquisition phase. While the right hand was used to move the mouse curser to click on the Corsi blocks during the recall phase. Handedness information was not collected from the study participants. Regardless of handedness, participants used their left and right hand to complete the two tasks. Neither task stressed speed or accuracy, that is, the interest area where accurate responses were obtained from for each Corsi block target was made large enough to correctly record target selections, and the auditory tone discrimination task allowed participants 750 ms to respond to the tones presented. Therefore, it is unlikely that handedness would influence the results.

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 (i.e., 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).

$$\mathbf{DTC} = \mathbf{D} - \mathbf{S}/\mathbf{S}$$

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).

Statistical analysis

A two-sample t-test was conducted to determine if the frequency of post-concussion symptoms was different between the two groups (concussion, no-concussion). A paired t-test was conducted using both administrations of the tone discrimination task (i.e., auditory-single1 vs. auditory-single2) to assess reliability and rule out practice effects. A 2-way, mixed 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. This analysis was conducted to explore any trend 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 auditory cost distribution is negatively skewed because the non-concussed participants' auditory cost was significantly lower compared to participants with a history of concussion.

Results

The two-sample t-test on symptom frequency showed no significant differences between the groups (see Table 1). Further analysis showed no significant group differences in somatic, cognitive or emotional symptoms on the Waterloo and ImPACT 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 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 prioritise the Corsi block test, we expected no differences in Corsi performance between task conditions.

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 condition and concussion history (F (1, 27) = 17.01, P < .001; see Figure 2). *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 (No-concussion: 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 (No-concussion: M = 87.91%, SD = 9.01; concussion: M = 87.65%, SD = 4.64).

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 eight females with a history

Table 2. Statistical results for performance accuracy on the Corsi Block test.

Corsi block memory span			
Effects	*DF*	*F*	*p*
Concussion (no-concussion, concussion)	1, 27	0.02	.88
Task (single, dual)	1, 27	1.85	.19
Task*concussion	1, 27	0.10	.76

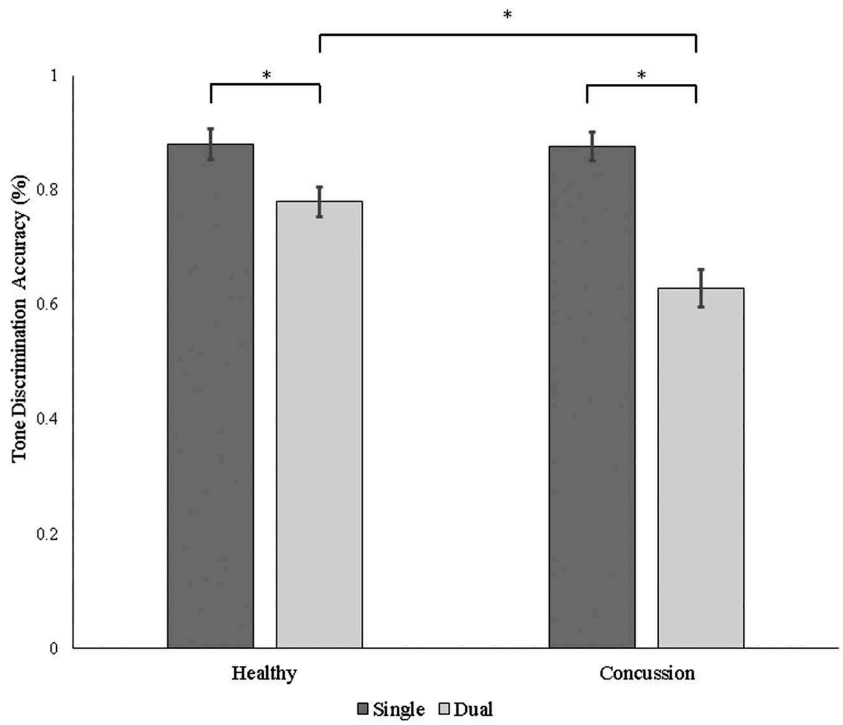

Figure 2. Mean tone discrimination accuracy obtained during the single and dual task plotted for the two groups of participants (i.e., no concussion, concussion). Participants with a history of concussion had a significantly lower tone accuracy when performing the dual task in comparison to the no-concussion participants ($P < 0.05$). Error bars represent standard error of the mean.

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 (No-concussion: $M = 80.75\%$, SD = 10.24; concussion: $M = 85.20\%$, SD = 13.43) compared to the females (No-concussion: $M = 92.28\%$, SD = 4.64; concussion: $M = 90.63\%$, SD = 4.92). In the dual-task condition, tone discrimination accuracy was reduced in both groups: males (No-concussion: $M = 70.75\%$, SD = 10.69; concussion: $M = 60.90\%$, SD = 15.62) and females (No-concussion: $M = 82.14\%$, 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 3). In contrast, removing the 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, $P = .19$.

Discussion

To our knowledge, the present study is the first to explore executive functions in a sample of young adult intercollegiate varsity ice hockey players with and without a history of concussion. Experimental results showed that athletes with a history of concussion had a greater difficulty with dividing attention between two tasks compared to their non-concussed peers. Executive functions were assessed using an experimental dual-task paradigm that included a 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. Furthermore, 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.

A well-recognised, cognitive psychological model that can be used 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 prioritising 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 that deficits in the central executive function may be explained by concussion history because athletes with a history of concussion had more difficulty in dividing attention between the Corsi block

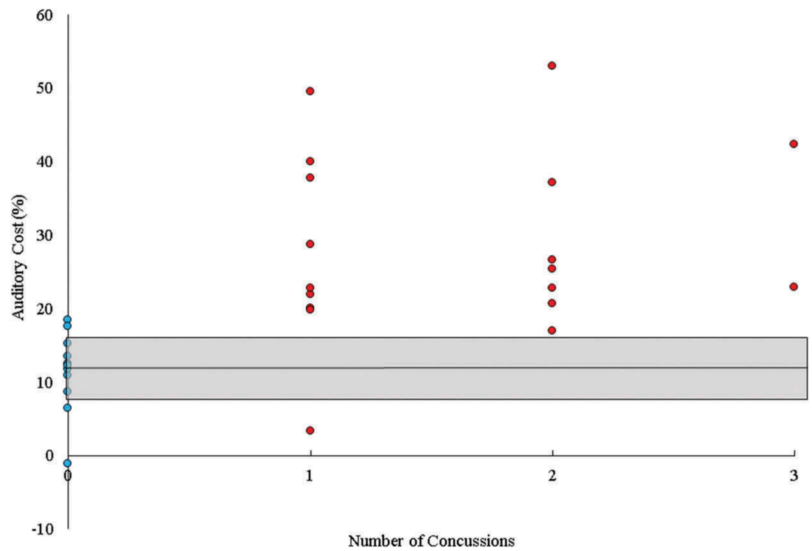

Figure 3. Individual auditory cost as a function of a number of concussions. Participants without a history of concussions are indicated by the blue symbols and the grey, shaded area indicates the 95% confidence interval for the mean for control participants. Seventeen out of 18 participants with a history of at least one concussion had an auditory cost that fell outside of the 95% confidence interval.

test and the auditory tone discrimination task. Importantly, the deficit was only significant when task demands were stressed in the dual-task condition.

Our research paradigm required participants to divide attention between two tasks, a process controlled by executive functions. The current results extend previous research by Bernstein (2002), who reported that a history of concussion affects one's ability to perform two tasks simultaneously. In contrast to the previous study which involved a mixed population of athletes and non-athletes, we examined varsity intercollegiate ice hockey players with a similar sport-specific training background. Thus, our results may have greater generalizability to team-sport athletes because they must use executive functions to process visual and auditory information quickly (i.e., differentiating teammates from opposition) during dynamic game situations. Previous literature (Vestberg et al., 2012; Voss, Kramer, Basak, Prakash & Roberts, 2010) has shown that athletes outperform non-athletes on attentional paradigms testing executive functions suggesting that athletes develop higher-level cognitive skills from years of competitive sports training. For instance, contact sport athletes frequently compete in fast-paced environments which require memory, attention and decision making skills (Voss et al., 2010). Therefore, it is important that studies investigating the effect of concussions on executive functions focus on examining athletes within the same sport domain to avoid confounds with different sports. Additionally, more sensitive tasks involving visual and auditory information may provide greater insight into revealing cognitive deficits post-concussion.

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 five time points (72 h, 1 week, 2 weeks, 1 month and 2 months), this research provided insight into the long-term impairments that may persist when concussion symptoms disappear (i.e., 2 weeks–1 month). 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. Similar to Howell et al. (2013), we used a task to test executive functions in athletes. In contrast to Howell et al. (2013), we examined young adult varsity athletes (ages 18–25) that had suffered a concussion more than 2 months ago and had returned to play without symptoms. Our findings showed 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. Specifically, the performance of an auditory discrimination task under a high cognitive load was impaired following a concussion compared to athletes with no concussions. These results may have implications when athletes are placed in contact sport environments where they are required to attend to teammates' voices, which is a more complex cognitive process, and process complex visuospatial information. It is possible that a previously concussed athlete may have trouble accurately processing their environment, which may increase the probability of sustaining another injury. Therefore, cognitively demanding tasks testing executive functions may provide more insight into the potential long-term effects of concussions.

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, 2005). 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 et al., 2005; 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., 2005). 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.

The current study has three main limitations, including an unbalanced design for concussions, a small sample size to test sex differences and a cross-sectional design. In our study, nine participants had a history of one concussion, seven with a history of two concussions and two with a history of three or more concussions. Thus, we did not have the power to test whether the number of concussions affected dual-task performance. However, we did find similar results to Bernstein (2002) who reported no relationship between dual-task performance and the number of concussions or the time since last concussion.

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 (Colvin et al., 2009; Covassin, Schatz, & Swanik, 2007; Covassin et al., 2006). 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 (Colvin et al., 2009; Covassin et al., 2007, 2006). 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., 2009; Covassin et al., 2007).

Finally, our cross-sectional design shows a relation between concussion history and lower performance on the dual task; however, it cannot be determined whether the reduction in executive functions resulted from a concussion or if lower executive functions led to the concussion. Longitudinal research will help to resolve this question. 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 overreport their history of concussion as many concussions are unrecognised and underreported (Llewellyn, Burdette, Joyner, & Buckley, 2014). Therefore, future research should continue to address our limitations because some evidence has suggested that the number of concussions is associated with a reduced performance on neuropsychological tests (De Beaumont, Brisson, Lassonde & Jolicoeur, 2007; Iverson et al., 2004), and that sex-related variables (i.e., hormonal) can affect recovery patterns (Colvin et al., 2009; Covassin et al., 2007).

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 (CogState Ltd, Victoria, Australia) and the HeadMinder Concussion Resolution Index (HeadMinder, Inc, New York, NY). 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.

Conclusion

Results from this study show that athletes with similar sport training experience and a history of sports-related concussion have a greater difficulty dividing attention between two tasks presented simultaneously compared to athletes with no-concussion history. Assessments stressing cognitive processes of attention are useful in discriminating athletes with and without a history of concussion in the long term.

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References

Anderson, V., Jacobs, R., & Anderson, P. J. (Eds.). (2011). *Executive functions and the frontal lobes: A lifespan perspective*. Hove: Psychology Press.

Baddeley, A. (1992). Working memory. *Science*, *255*(5044), 556–559. doi:10.1126/science.1736359

Baddeley, A. D., & Hitch, G. (1974). Working memory. In G.H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 8, pp. 47–89). New York: Academic Press.

Berch, D. B., Krikorian, R., & Huha, E. M. (1998). The Corsi block-tapping task: Methodological and theoretical considerations. *Brain and Cognition*, *38*(3), 317–338. doi:10.1006/brcg.1998.1039

Bernstein, D. M. (2002). Information processing difficulty long after self-reported concussion. *Journal of the International Neuropsychological Society*, *8*(5), 673–682. doi:10.1017/S1355617702801400

Beurskens, R., & Bock, O. (2012). Age-related deficits of dual-task walking: A review. *Neural Plasticity*, *2012*, 1–9. doi:10.1155/2012/131608

Broglio, S. P., Macciocchi, S. N., & Ferrara, M. S. (2007). Neurocognitive performance of concussed athletes when symptom free. *Journal of Athletic Training*, *42*(4), 504–508. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2140076/?report=classic

Catena, R. D., van Donkelaar, P., & Chou, L.-S. (2007). Cognitive task effects on gait stability following concussion. *Experimental Brain Research*, *176*(1), 23–31. doi:10.1007/s00221-006-0596-2

Catena, R. D., van Donkelaar, P., & Chou, L.-S. (2009). Different gait tasks distinguish immediate vs. long-term effects of concussion on balance control. *Journal of Neuroengineering and Rehabilitation*, *6*, 25. doi:10.1186/1743-0003-6-25

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

Chaput, G., Giguère, J.-F., Chauny, J.-M., Denis, R., & Lavigne, G. (2009). Relationship among subjective sleep complaints, headaches, and mood alterations following a mild traumatic brain injury. *Sleep Medicine*, *10*(7), 713–716. doi:10.1016/j.sleep.2008.07.015

Chein, J. M., Ravizza, S. M., & Fiez, J. A. (2003). Using neuroimaging to evaluate models of working memory and their implications for language processing. *Journal of Neurolinguistics*, *16*(4–5), 315–339. doi:10.1016/S0911-6044(03)00021-6

Chen, J.-K., Johnston, K. M., Collie, A., McCrory, P., & Ptito, A. (2007). A validation of the post-concussion symptom scale in the assessment of complex concussion using cognitive testing and functional MRI. *Journal of Neurology, Neurosurgery & Psychiatry*, *78*(11), 1231–1238. doi:10.1136/jnnp.2006.110395

Colvin, A. C., Mullen, J., Lovell, M. R., West, R. V., Collins, M. W., & Groh, M. (2009). The role of concussion history and gender in recovery from soccer-related concussion. *The American Journal of Sports Medicine*, *37*(9), 1699–1704. doi:10.1177/0363546509332497

Corsi, P. M. (1972). *Human memory and the medial temporal region of the brain*. Montreal, Quebec: McGill University.

Cossette, I., Ouellet, M.-C., & McFadyen, B. J. (2014). A preliminary study to identify locomotor-cognitive dual tasks that reveal persistent executive dysfunction after mild traumatic brain injury. *Archives of Physical Medicine and Rehabilitation*, *95*(8), 1594–1597. doi:10.1016/j.apmr.2014.03.019

Covassin, T., Schatz, P., & Swanik, C. B. (2007). Sex differences in neuropsychological function and post-concussion symptoms of concussed collegiate athletes. *Neurosurgery*, *61*(2), 345–351. doi:10.1227/01.NEU.0000279972.95060.CB

Covassin, T., Swanik, C. B., Sachs, M., Kendrick, Z., Schatz, P., Zillmer, E., & Kaminaris, C. (2006). Sex differences in baseline neuropsychological function and concussion symptoms of collegiate athletes. *British Journal of Sports Medicine*, *40*(11), 923–927. doi:10.1136/bjsm.2006.029496

Daneshvar, D. H., Nowinski, C. J., McKee, A. C., & Cantu, R. C. (2011). The epidemiology of sport-related concussion. *Clinics in Sports Medicine*, *30*(1), 1–17. doi:10.1016/j.csm.2010.08.006

De Beaumont, L., Brisson, B., Lassonde, M., & Jolicoeur, P. (2007). Long-term electrophysiological changes in athletes with a history of multiple concussions. *Brain Injury*, *21*(6), 631–644. doi:10.1080/02699050701426931

Dougan, B. K., Horswill, M. S., & Geffen, G. M. (2014). Athletes' age, sex, and years of education moderate the acute neuropsychological impact of sports-related concussion: A meta-analysis. *Journal of the International Neuropsychological Society*, *20*(01), 64–80. doi:10.1017/S1355617712001464

Dziemianowicz, M. S., Kirschen, M. P., Pukenas, B. A., Laudano, E., Balcer, L. J., & Galetta, S. L. (2012). Sports-related concussion testing. *Current Neurology and Neuroscience Reports*, *12*(5), 547–559. doi:10.1007/s11910-012-0299-y

Fait, P., Swaine, B., Cantin, J.-F., Leblond, J., & McFadyen, B. J. (2013). Altered integrated locomotor and cognitive function in elite athletes 30 days postconcussion: A preliminary study. *The Journal of Head Trauma Rehabilitation*, *28*(4), 293–301. doi:10.1097/HTR.0b013e3182407ace

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

Halterman, C. I., Langan, J., Drew, A., Rodriguez, E., Osternig, L. R., Chou, L. S., & van Donkelaar, P. (2006). Tracking the recovery of visuospatial attention deficits in mild traumatic brain injury. *Brain*, *129*(3), 747–753. doi:10.1093/brain/awh705

Howell, D., Osternig, L., Van Donkelaar, P., Mayr, U., & Chou, L.-S. (2013). Effects of concussion on attention and executive function in adolescents. *Medicine & Science in Sports & Exercise*, *45*(6), 1030–1037. doi:10.1249/MSS.0b013e3182814595

Howell, D. R., Osternig, L. R., Koester, M. C., & Chou, L.-S. (2014). The effect of cognitive task complexity on gait stability in adolescents following concussion. *Experimental Brain Research*, *232*(6), 1773–1782. doi:10.1007/s00221-014-3869-1

Iverson, G. L., Gaetz, M., Lovell, M. R., & Collins, M. W. (2004). Cumulative effects of concussion in amateur athletes. *Brain Injury*, *18*(5), 433–443. doi:10.1080/02699050310001617352

Kessels, R. P., Van Zandvoort, M. J., Postma, A., Kappelle, L. J., & De Haan, E. H. (2000). The Corsi block-tapping task: Standardization and normative data. *Applied Neuropsychology*, *7*(4), 252–258. doi:10.1207/S15324826AN0704_8

Kleffelgaard, I., Roe, C., Soberg, H. L., & Bergland, A. (2012). Associations among self-reported balance problems, post-concussion symptoms and performance-based tests: A longitudinal follow-up study. *Disability and Rehabilitation*, *34*(9), 788–794. doi:10.3109/09638288.2011.619624

Kontos, A. P., Covassin, T., Elbin, R. J., & Parker, T. (2012). Depression and neurocognitive performance after concussion among male and female high school and collegiate athletes. *Archives of Physical Medicine and Rehabilitation*, *93*(10), 1751–1756. doi:10.1016/j.apmr.2012.03.032

Llewellyn, T., Burdette, G. T., Joyner, A. B., & Buckley, T. A. (2014). Concussion reporting rates at the conclusion of an intercollegiate athletic career. *Clinical Journal of Sport Medicine*, *24*(1), 76–79. doi:10.1097/01.jsm.0000432853.77520.3d

Locklin, J., Bunn, L., Roy, E., & Danckert, J. (2010). Measuring deficits in visually guided action post-concussion. *Sports Medicine*, *40*(3), 183–187. doi:10.2165/11319440-000000000-00000

Lovell, M. R. (2011). *Immediate post-concussion assessment testing test: Clinical interpretive manual*. Pittsburg, PA: ImPACT Applications.

Martini, D. N., Sabin, M. J., DePesa, S. A., Leal, E. W., Negrete, T. N., Sosnoff, J. J., & Broglio, S. P. (2011). The chronic effects of concussion on gait. *Archives of Physical Medicine and Rehabilitation*, *92*(4), 585–589. doi:10.1016/j.apmr.2010.11.029

McClincy, M. P., Lovell, M. R., Pardini, J., Collins, M. W., & Spore, M. K. (2006). Recovery from sports concussion in high school and collegiate athletes. *Brain Injury*, *20*(1), 33–39. doi:10.1080/02699050500309817

McCrory, P., Meeuwisse, W. H., Aubry, M., Cantu, B., Dvorak, J., Echemendia, R. J., … Turner, M. (2013). Consensus statement on concussion in sport: The 4th international conference on concussion in sport held in Zurich, November 2012. *British Journal of Sports Medicine*, *47*(5), 250–258. doi:10.1136/bjsports-2013-092313

Notebaert, A. J., & Guskiewicz, K. M. (2005). Current trends in athletic training practice for concussion assessment and management. *Journal of Athletic Training*, *40*(4), 320.

Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience*, *35*, 73–89. doi:10.1146/annurev-neuro-062111-150525

Ptito, A., Chen, J. K., & Johnston, K. M. (2007). Contributions of functional magnetic resonance imaging (fMRI) to sport concussion evaluation. *NeuroRehabilitation*, *22*(3), 217–227. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/17917172

Sauseng, P., Klimesch, W., Schabus, M., & Doppelmayr, M. (2005). Fronto-parietal EEG coherence in theta and upper alpha reflect central executive functions of working memory. *International Journal of Psychophysiology*, *57*(2), 97–103. doi:10.1016/j.ijpsycho.2005.03.018

Schatz, P., Pardini, J. E., Lovell, M. R., Collins, M. W., & Podell, K. (2006). Sensitivity and specificity of the ImPACT test battery for concussion in athletes. *Archives of Clinical Neuropsychology*, *21*(1), 91–99. doi:10.1016/j.acn.2005.08.001

Vandierendonck, A., Kemps, E., Fastame, M. C., & Szmalec, A. (2004). Working memory components of the Corsi blocks task. *British Journal of Psychology*, *95*(1), 57–79. doi:10.1348/000712604322779460

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

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

Wager, T. D., & Smith, E. E. (2003). Neuroimaging studies of working memory:. *Cognitive, Affective, & Behavioral Neuroscience*, *3*(4), 255–274. doi:10.3758/CABN.3.4.255

Appendix

University of Waterloo Health History Questionnaire:

Health History Questionnaire

Participant:____________________ M/F
D.O.B.:______________(mm/dd/yyyy)

Date:______________________
Team/Position:______________________

1. At what age did you begin playing organized sport? _______

2. How many years have you played your sport? _______

3. Do you wear a mouth guard while playing?
___yes ___no
If yes, what kind?
___stock ___boil & bite
___custom, front teeth ___custom, all

4. Have you suffered from neck pain within the past 6 months? ___yes ___no

5. Have you suffered a concussion?
___yes ___no ___not sure

6. If yes to #5,
a) How many times total? _____
b) How many times while playing sport in the past 6 months? _____
c) Date of last concussion? ____________
d) How long did the symptoms last (for last concussion)?
___1-3 days ___4-7 days ___8-10 days
___11-14 days ___more than 2 weeks
e) After the last concussion, how long did you refrain from physical activity?
___4-7 days ___8-10 days ___11-14 days
___15-21 days ___more than 3 weeks

7. Have you ever been knocked unconscious?
___yes ___no

8. If yes to #7,
a) How many times in the past 6 months? ___
b) What is the longest duration you've been knocked unconscious? ____________

9. In the past 6 months, after being hit in the head in sports, have you experienced any of the following symptoms:
___confusion ___getting 'dinged'
___headaches ___balance problem
___nausea ___getting 'bell rung'
___dizziness ___ringing in the ears
___blurry vision ___poor memory
___other:____________________

10. In regards to how you feel NOW, please rate the following:

	None	Mild					Severe
Headache	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	5	6
Neck pain	0	1	2	3	4	5	6
Nausea/vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	5	6
Hard to concentrate	0	1	2	3	4	5	6
Feeling "in a fog"	0	1	2	3	4	5	6
Trouble remembering	0	1	2	3	4	5	6
Fatigue/low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
Trouble falling asleep	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervous/anxious	0	1	2	3	4	5	6

11. Do the above symptoms get worse with physical activity? ___yes ___no

12. Do the above symptoms get worse with mental activity? ___yes ___no