Examining behavioural and electrophysiological markers of mental workload in individuals with and without a history of concussion

by

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Author’s Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the 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.

Statement of Contributions

I declare that I was the main author for all writing of the thesis and main contributor of the research design, data collection, data analysis and data interpretation, which were performed under the supervision of Dr. Ewa Niechwiej-Szwedo. Sections 1 and 6 were not written for publication. Dr. Ewa Niechwiej-Szwedo was the primary co-author on all published manuscripts which were derived from this thesis. Dr. Richard Staines was the secondary co-author on studies one and two in this manuscript.

Abstract

Objectives: The goal of this thesis was to examine the neurocognitive mechanisms of mental workload for the purpose of improving our knowledge of the long-term effects of concussion. Four experiments were performed manipulating mental workload in individuals with and without a history of concussion. Studies one and two increased mental workload by manipulating set size (i.e., number of items to be remembered) and task condition (single-task, dual-task) in individuals with and without a history of concussion, respectively. In addition, event-related potentials (ERPs) were recorded to examine the neural correlates of information processing that are affected by mental workload. Study three examined mental workload by changing the requirements of the task through the manipulation of pattern configuration characteristics. The fourth study examined mental workload in individuals with and without a history of concussion using three types of workload manipulation: set size, task condition, and pattern configuration complexity.

Methods: Thirty-six participants (20 no-concussion, 16 asymptomatic) were recruited for studies one and two, and assessed using a dual-task paradigm involving a computerised eCorsi block task and auditory oddball task that progressively increased in workload (i.e., set size, task condition). ERPs were used to study the sensory and cognitive stages of information processing as a function of mental workload. Seventeen participants (14 no-concussion, 3 asymptomatic) were tested in study three using a computer and phone version of the eCorsi task, which manipulated workload by changing the average angle of a patterns at set sizes of five to eight blocks. Study four examined secondary auditory oddball performance as a function of eCorsi pattern complexity in nineteen participants (9 no-concussion, 10 asymptomatic).

Results: The no concussion group showed reduced eCorsi recall accuracy as set size increased, which was maintained between task conditions (single, dual). In contrast, auditory oddball performance decreased (i.e., poorer accuracy, longer response times [RTs]) as mental workload increased (task, set size). ERP's showed amplitude reductions in early sensory (P50) and later cognitive (P300) potentials when both tasks were performed simultaneously compared to alone. In contrast, later sensory (N100) ERP increased in amplitude. Sensory gating was consistent at both P50 and N100 potentials as a function of mental workload. The concussion history group showed poorer auditory (lower accuracy, more errors of commission, and longer RTs) when both tasks were performed simultaneously whereas no between-group differences were found on the eCorsi task. ERPs indicated poorer sensory gating (P50, N100) and cognitive processing (i.e., reduced P300 amplitude) in the asymptomatic group, which changed as a function of workload. Investigating the properties of the dual-task showed reduced eCorsi recall accuracy in hard patterns (smaller angles, more crosses, and longer distances) compared to easy patterns; however, this did not affect auditory oddball measures.

Conclusions: Sensory and cognitive processes change as a function of mental workload (task, set size) and in those with a history of concussion suggesting these individuals have problems gating in important information, which may affect the efficiency of later cognitive processes and subsequent behavioural performance. Importantly, mental workload can be increased by task condition (single, dual), set size (# of items to remember), and path configuration difficulty (easy, hard), which reflect different types of load. These findings are particularly useful in the development of sensitive neurocognitive tests for identifying persisting deficits in individuals with a history of concussion.

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List of Abbreviations

AD – Alzheimer's Disease

AN – Attention Network

BOLD – Blood Oxygen – Level Dependent

CBTT – Corsi Block Tapping Task

CT – Computerized Tomography

DLPFC – Dorsolateral Prefrontal Cortex

DTI – Diffuse Tensor Imaging

EB – Episodic Buffer

EEG – Electroencephalography

EF – Executive Functions

ERP – Event-Related Potentials

FA – Fractional Anisotropy

FMRI – Functional Magnetic Resonance Imaging

MHI – Mild Head Injury

MGB – Medial Geniculate Body

MVA – Motor Vehicle Accident

PFC – Prefrontal Cortex

PTS – Post Traumatic Symptoms

PL – Phonological Loop

TBI – Traumatic Brain Injury (mTBI – mild)

TRN – Thalamic Reticular Nucleus

VSSP – Visuospatial Sketchpad

Section 1: General Introduction

1.1 Significance of traumatic brain injury

Difficulties in performing multiple tasks, remembering important information, and problems making timely decisions are common signs of age-related cognitive decline (Buckner, 2004; Macpherson, Phillips, & Sala, 2002). Unfortunately, these cognitive difficulties are also seen in young (18-29 years; Horneman & Emanuelson, 2009) and middle-aged adults (30-64 years; Moretti et al., 2012; Niogi et al., 2008) following a traumatic brain injury (TBI) resulting from sports-related impact, accidental falls, or motor vehicle accidents (Langlois, Rutland-Brown & Walk, 2006). Many studies using current clinical neuropsychological tests and standard neuroimaging methods (i.e., computed tomography, magnetic resonance imaging) do not detect any long-term (i.e., months to years) cognitive or structural abnormalities in individuals who are asymptomatic and returned to regular activity following a concussion, a mild form of TBI (Belanger, Vanderploeg, Curtiss, & Warden, 2007; Broglio, Pontifex, O'Connor, & Hillman, 2009; Broglio, Ferrara, Piland, & Anderson, 2006; Maerlender et al., 2010; Perlstein et al., 2004). These findings would lead us to believe that concussions do not contribute to any long-term effects. However, a growing body of research has shown that despite no differences detected using current clinical neuropsychological assessments, concussions often result in long-term subtle deficits in executive control (Bernstein, 2002; Howell et al., 2013; Pontifex, O'Connor, Broglio, & Hillman, 2009; Tapper, Gonzalez, Roy & Niechwiej-Szwedo, 2017), and altered electrophysiological measures of neural function (Adams, 2018; Bernstein, 2002; Broglio et al., 2009; De Beaumont et al., 2009; Duncan et al., 2003, 2005; Gosselin et al., 2006; Rousseff et al., 2006; Segalowitz, Bernstein, & Lawson, 2001; Ruiter et al., 2019). This discrepancy may arise because standard clinical assessments are composed of tasks that impose a mental workload which does not sufficiently challenge a person's cognitive abilities resulting in similar performance outcomes between individuals with and without a history of concussion. As a result, subtle deficits that may hinder an individual's real life performance (i.e., work, school, sports) and increase their susceptibility to late-life neurodegenerative diseases such as dementia (Gavett, Stern, Cantu, Nowinski, & McKee, 2010; Gottlieb, 2000; Plassman et al., 2000), may go unrecognized. For that reason, development and validation of sensitive diagnostic tools that can reliably identify individuals experiencing altered cognitive function following a concussion is imperative so proper rehabilitation methods can be targeted. Therefore, the research in this thesis was conducted to develop a better understanding of the long-term behavioural and electrophysiological abnormalities in individuals with a history of concussion using a test that progressively varies mental workload. In addition, the psychometric properties of the task were examined to determine its reliability for potential use in clinical practice.

Literature Review

1.2 Concussion

1.2.1 Definition

Concussion is a traumatic brain injury resulting in a temporary disruption of neurological functioning accompanied by a variety of acute symptoms that can last minutes to hours (McCrory et al., 2017). The majority of these symptoms are short-lived (7-10 days post injury), and likely reflect a temporary functional disruption rather than a structural injury (McCrory et al., 2017; Sharp & Jenkins, 2015); however, in some instances symptoms may persist. In addition, growing evidence suggests that concussions can result in chronic cognitive dysfunction

(Bernstein, 2002; Howell et al., 2013; Tapper et al., 2017). Concussions can occur by any biomechanical forces to the head or body (e.g., motor vehicle accidents, falls, being hit) that causes the brain to 'shake' within the skull. Typically, concussions are categorized as a TBI and interchangeably referred to as a mild TBI in the literature. However, concussion does not distinguish between grades of severity and may result in neuropathological changes (McCrory et al., 2017). For this thesis, the term concussion will be used in accordance with the definition provided by McCrory and colleagues (2017) at the 5th international conference on concussion in sport. This definition includes a disruption to one or more of the following domains: (1) somatic (i.e., headache, nausea), cognitive (i.e., feeling in a fog, sensitivity to light) or emotional symptoms (i.e., irritability, sadness), (2) physical signs (i.e., loss of consciousness, amnesia) or (3) cognitive impairment (i.e., slowed reaction time, memory deficits). Terminology used in this document will be held consistent with what was presented in the original research articles.

1.2.2 *Acute neural mechanisms affected by concussion*

Acute (i.e., the initial period up to 7-days after sustaining a concussion) functional impairments following a concussion are well reported despite little evidence supporting any structural changes (Bazarian, Blyth, & Cimpello, 2006; Elbin, Schatz, Lowder, & Kontos, 2014), McCrory et al., 2017). For instance, structural neuroimaging tools such as computerized tomography (CT) scans or magnetic resonance imaging (MRI) often do not show structural damage following a concussion. For that reason, medical professionals rely on behavioural tests to diagnose and determine return-to-play procedures including evaluation of balance, subjective report of symptoms, and neurocognitive assessment of executive functions. Research shows that these neurocognitive assessments (e.g., Immediate Post-concussion Assessment and Cognitive

Test, Headminder Resolution Index) are useful in identifying cognitive dysfunction within the acute phase post-concussion; however, cognitive function typically returns to ‘normal’ or baseline within 10 days post-concussion (Iverson, Brooks, Collins, & Lovell, 2006; Schatz et al., 2006; Schatz & Zillmer, 2003). The exact mechanism(s) contributing to the temporary disturbance of cognitive dysfunction and symptomology have yet to be identified; however, it is hypothesized that a cascade of neurochemical events arise from the biomechanical forces applied to the brain (see detailed description provided by MacFarlane & Glenn, 2015). In particular, animal models indicate that axonal stretching and shearing leads to a disruption in cellular membranes causing an imbalance in cellular homeostasis. As a result, cellular acidity levels increase causing cellular damage, a disruption of the blood-brain barrier and cerebral edema. In humans, studies show cellular microstructure damage in the acute phase using less conventional imaging techniques such as, functional Magnetic Resonance Imaging (fMRI) and Diffuse Tensor Imaging (DTI) (see review by Gardner et al., 2012). For instance, these studies report increased axonal swelling and damaged white matter tract integrity in different brain regions (e.g., corpus collasum, corticospinal tract; prefrontal cortex) following a concussion. Interestingly, white matter damage can persist weeks to months post-injury despite individuals being asymptomatic and cognitive functioning returning to normal (Churchhill et al., 2019). These findings indicate that persistent neurocognitive effects of a concussion could manifest in behavioural assessments.

1.2.3 *Chronic neural mechanisms affected by concussion*

There is a growing body of research showing significant changes in brain function in individuals with a history of concussion who are asymptomatic in the chronic phase (i.e., >1 year post-concussion; Martini & Broglio, 2018) using imaging techniques such as fMRI, DTI and electroencephalography (EEG). These tools, paired with neurocognitive tests, have provided an important insight into the neural mechanisms contributing to the long-term cognitive dysfunction following a concussion.

Functional MRI examines neuronal activation by calculating the blood oxygen-level dependent (BOLD) signal from either increased blood perfusion or reduced deoxyhemoglobin levels. There is growing evidence showing hyperactivation or hypoactivation in different brain regions in individuals with a history of concussion in the long-term who are asymptomatic (Ford, Giovanello, & Guskiewicz, 2013; Churchill et al., 2017; Terry, Adams, Ferrara, & Miller, 2015). For instance, Churchill and colleagues (2017) found hyperactivation of the prefrontal cortex and motor cortex and, hypoactivation in the limbic system during resting-state fMRI in a group of asymptomatic team sport athletes with a history of concussion (9-120 months post) compared to athletes without a concussion. Furthermore, Terry and colleagues (2015) found hypoactivation in the inferior/ middle frontal gyri and angular gryus in a group of football players with a history of concussion (>15 years) when performing a verbal working memory task compared to a group of non-concussed athletes. The authors suggested that sustaining multiple concussions may be associated with subtle changes in memory encoding and retrieval. Importantly, they found no differences in behavioural performance between groups on several neuropsychological measures (e.g., Weschler memory scale and test of adult reading, California verbal learning test). Possibly, these tasks were not difficult enough to reveal differences in behavioural performance between the groups despite changes in neuronal functioning. In summary, results from fMRI studies provide some insight into what areas of the brain may be affected following a concussion. However, these studies have not been able to find a correlation between the pattern of brain activation measured by fMRI and behavioural performance.

Diffuse tensor imaging (DTI) is another imaging technique used to gain insight into the neural functioning in individuals with a history of concussion. DTI is an MRI-based tool that creates images of the brain's white matter tracts by measuring the diffusion of water in the tissue. Fractional anisotropy (FA) and mean diffusivity (MD) are the most common measurements of microstructural integrity. Fractional anisotropy (FA) is a measure of the directionality of water molecules in a tissue where lower FA values (i.e., closer to 0) are interpreted as less myelination, smaller axon diameter and reduced fiber density, and higher FA values (i.e., closer to 1) reflect heavily myelinated, larger axon diameter, and increased fiber density. Mean diffusivity (MD) is a measure of the rate of water diffusion where higher MD values are interpreted as greater free diffusion resulting from damaged tissue. Studies examining FA or MD in concussion (or mTBI) patients have found either higher (Henry et al., 2011; Mayer et al., 2010; Sasaki et al., 2014) or no difference (Inglese et al., 2005; Meier et al., 2016) compared to controls. For example, Henry and colleagues (2011) found increased FA in the corpus callosum and dorsal regions underlying premotor and sensory cortices in the same group of football players who were tested at 5 days and 6 months post-concussion compared to controls. These FA increases were thought to reflect cytotoxic edema (i.e., brain cell swelling) and localized inflammation in the acute phase (5 days) and, volume loss in cross fibers in the longer-term phase (6 months). Unfortunately, they did not report whether symptomology returned to normal at the 6-month period or report any behavioural performance measures. Additional research has shown increases in frontal and temporal FA in varsity hockey players who experienced a concussion at a minimum 6-months prior compared to sport matched controls (Sasaki et al., 2014). The authors suggested that persisting FA increases may reflect an increased number of microglial cells or long-lasting neuroinflammation, a common process occurring after a TBI (Gentleman et al., 2004).

Interestingly, groups did not differ on neuropsychological measures including, the Immediate Postconcussion Assessment and Cognitive Test (ImPACT) or the Sport Concussion Assessment Tools-2 (SCAT2). Lastly, Ting and colleauges (2016) found no difference in FA between controls, acute mTBI and those suffering from chronic post traumatic symptoms (PTS); however, those with acute mTBI had significantly greater MD in the splenium of corpus collasum compared to controls whereas those with chronic PTS had significantly lower MD. These contrasting results using DTI measures such as FA and MD may be due to the potential misdiagnosis of TBI severity or the difference in brain regions tested. Nevertheless, imaging results in the chronic phase suggest that concussions are a complex injury that result in changes to the white matter tracts within multiple cortical and sub-cortical networks.

One of the most widely used techniques to better understand brain functioning after a concussion is electroencephalography (EEG). EEG is a non-invasive tool that records cortical excitability from the scalp using surface electrodes encompassed in a mesh cap. One approach to analyzing EEG has focused on event-related potentials (ERPs), which examine a small positive (P) or negative (N) voltage change at the scalp that is produced by the summation of postsynaptic graded potentials firing in synchrony in response to an event or stimulus (Sur & Sinha, 2009). ERPs are typically identified with respect to their temporal (i.e., latency), spatial (i.e., electrode placement), and size (i.e., amplitude) characteristics and can be used to provide insight into the cortical mechanisms of sensory and cognitive information processing.

Many studies have identified abnormalities in sensory (Adams, 2018; Duncan et al., 2003, 2005; Moore, Broglio, & Hillman, 2014; Tennant, 2018) and cognitive (Bernstein, 2002; Broglio et al., 2009; De Beaumont et al., 2006; Gosselin et al., 2006; Ozen, Itier, Preston, &

Fernandes, 2013; Rousseff et al., 2006; Segalowitz et al., 2001) ERPs in individuals who have suffered a sports-related concussion. For instance, Bernstein (2002) found decreased parietal P300 ERP amplitudes in asymptomatic individuals with a history of mild head injury experienced approximately eight years prior when they performed a visual-auditory dual-task compared to controls. Bernstein suggested this P300 ERP amplitude reduction was a deficit in information processing capacity or difficulty in allocating resources, which contributed to poorer dual-task performance in the concussion group. Additional research has provided evidence for cognitive processing deficits (i.e., P300 ERP amplitude reductions) in participants with a history of concussion ranging from a few months to multiple years on tasks requiring visual (Broglio et al., 2009) or auditory (De Beaumont et al., 2006; Gosseglin et al., 2006; Rousseff et al., 2006; Segalowitz et al., 2001) selective attention (i.e., two or three-stimulus oddball task) and working memory (i.e., n-back; Ozen et al., 2013). These findings suggest a reduction in the amount of attentional capacity, problems in efficiently allocating attentional resources, or troubles updating information into working memory. Other research has shown changes in early, sensory stages of information processing (i.e., auditory N100 or tactile N70) in individuals with a history of concussion when presented with stimuli in the tactile (Adams, Niechwiej-Szwedo, McIlroy, & Staines, 2020; Tenant, 2018) and auditory (Duncan et al., 2003, 2005; Gosselin et al., 2006; Ruiter et al., 2019; Segalowitz et al., 2001) domains. For example, Adams and colleagues (2020) showed larger N70 amplitudes to task-relevant tactile stimuli compared to irrelevant stimuli in a non-concussed population; in contrast, those with a history of concussion showed no difference between relevant and irrelevant stimuli. These results suggest that individuals with a history of concussion have difficulties with sensory gating, a process defined as the ability to either inhibit irrelevant information or facilitate relevant sensory information (Jones et al., 2016; Korzyukov et al., 2007). It is important to understand the interaction between sensory gating and cognitive processing because the efficacy to filter relevant from irrelevant information early in the sensory processing stream may influence attentional resources at the later, cognitive processing stage (Jones et al,. 2016). In addition, when attentional selection occurs at an early, sensory stage, more resources are available at the cognitive stage for other processes such as decision making or updating of working memory. One-way to study this is to use a test that progressively increases in mental workload such as increasing the number of items to be remembered (i.e., working memory) or performing two tasks simultaneously (i.e., divided attention) compared to alone. These types of tasks involve executive functions such as working memory and attention, and appear to be helpful in understanding the chronic cognitive impairments associated with a concussion. However, there has been limited research addressing how progressive increases in mental workload using tasks of executive functions affect sensory and cognitive processes. Therefore, more research into how information is processed as mental workload increases in individuals with and without a history of concussion can provide insight into the neural mechanisms affected by concussion in the long-term.

1.3 Executive Functions

The term executive functions (EFs) refers to a set of top-down cognitive processes that are necessary for controlling and coordinating behaviour, and have traditionally been associated with areas localized in the prefrontal lobe: the dorsolateral prefrontal cortex (DLPFC), orbitofrontal cortex, medial frontal cortex, and cingulate cortex (Diamond, 2014; Kane & Engle, 2002; Stuss & Knight, 2013; Szameitat, Lepsien, Von Cramon, Sterr, & Schubert, 2006). EFs are particularly important in complex environments where automatic reflexive actions would be detrimental or insufficient to performance, such as participating in sports or driving on a busy highway. Research has identified four core components of executive functions including *working memory* (WM) defined as the ability to maintain and manipulate information that has perceptually disappeared, *inhibition/interference control* defined as the ability to control one's attention by suppressing what is irrelevant and selecting what is important, *cognitive flexibility*, which builds on both working memory and inhibition and is defined as the ability to shift between multiple tasks or adapt to changing demands by inhibiting a previous goal and loading a new goal into working memory, and lastly, *divided attention* defined as the ability to perform two tasks concurrently (Diamond, 2014; Miyake et al., 2000). There has been continued debate whether these different EFs measure the same underlying cognitive mechanism (unity) or if they represent separable processes (diversity). Studies have identified that these EFs represent distinct but moderately correlated concepts (r =0.42-0.63) suggesting both unity and diversity of executive functions (Miyake et al., 2000).

Multiple tests have been used to characterise EFs showing their link with different aspects of life including school and job success (Bailey, 2007; St Clair-Thompson & Gathercole, 2006), physical and mental health (Miller, Barnes, & Beaver, 2011; Nigg et al., 2005), and overall quality of life (Brown & Landgraf, 2010; Sherman, Slick, & Eyrl, 2006). Extensive research shows that EFs progressively decline during normal aging (Kennedy & Raz, 2009), which can be further exacerbated following a TBI including a concussion (Lipton et al., 2009; Mangeot, Armstrong, Colvin, Yeates, & Taylor, 2002), or in neurological diseases such as dementia or Alzheimer's disease (Chiu et al., 2004; Johns et al., 2009). In particular, long-term deficits in working memory, inhibitory/interference control and divided attention have been reported in individuals who suffered a concussion (Bernstein, 2002; Howell, Buckley, Lynall, &

Meehan, 2018; Howell et al., 2013; Fait, Swaine, Cantin, Leblond, & McFadyen, 2013; Parker, Osternig, Van Donkelaar, & Chou, 2006; see review by Register-Mihalik, 2013; Tapper et al., 2017). Therefore, tasks stressing executive functions such as divided attention and working memory paired with EEG could be useful in revealing the underlying neurophysiological problems associated with a concussion.

1.3.1 Divided attention

Attention is the cognitive process of selectively focusing on information that is perceptually present or that is being held in working memory or retrieved from long-term memory (Anderson, 2005). It involves both bottom-up (i.e., salient stimuli from the environment) and top-down (i.e., goal-directed) processes. Divided attention is defined as the ability to perform two or more tasks simultaneously (i.e., dual-tasking) where multiple stimuli are presented at the same time within a modality or between different modalities (visual, auditory, tactile) (Kane & Engle, 2002; Register-Mihalik et al., 2013; Spelke, Hirst, & Neisser, 1976). The imposed mental workload increases when participants are instructed to perform two tasks concurrently that share similar processing resources (i.e., when more resources are dedicated to the primary task, fewer resources are available for the secondary task). On this account, secondary task performance measures become worse as evident in longer response times and/or more errors compared to when performing each task alone. However, research has demonstrated that humans are capable of simultaneously carrying out two tasks requiring different perceptual domains (i.e., verbal and visuospatial) in some situations resulting in little to no decline in the performance on either task (Baddeley and Hitch, 1974; Smyth and Scholey, 1994; Spelke et al., 1976). More recent research has confirmed and expanded on these findings suggesting that two tasks can be performed in parallel without affecting the efficacy of performance as long as the total processing capacity demands are not exceeded (Burnham, Sabia, & Langan, 2014; Morey & Cowan, 2005; Oberauer, Farrell, Jarrold, & Lewandowsky, 2016). As a result, dividing attention between two tasks does not always impose a greater workload as performance deficits are dependent on whether the tasks share similar resources (i.e., same perceptual domain) or the demands of the tasks exceed capacity.

1.3.2 Working Memory

Working memory (WM), a concept attributed to George Miller (1956), is defined as the amount of information that can be temporarily stored and immediately recalled. It is critical for understanding our current environment by holding information active in mind and using it to make decisions about the ongoing situation. Over the past six decades, monumental studies performed by Atkinson and Shiffrin (1968) and Baddeley and Hitch (1974) have advanced our knowledge of working memory from a unitary store to a multi-component model. Baddeley and Hitch (1974) conceptualized working memory as a limited capacity system involving three-components including a *central executive* - a supervisory control system responsible for allocating attentional resources to incoming information to be stored within two underlying slave systems: the *visuospatial sketchpad* (VSSP) and the *phonological loop* (PL). A fourth component, the *episodic buffer*, was later added to describe how visual and verbal information could be combined together into ‘chunks’ to create a single episode/event (Baddeley, 2003) and provided a link to long-term memory where current information could be related with previously learned information. This thesis will focus on two tasks within the VSSP, which is responsible for storing and processing visuospatial information such as scenes, colours, shapes and their locations (Luck & Vogel, 2013) as opposed to the PL, which handles the storage and processing of phonological (verbal) information such as words, sentences and numbers.

1.3.3 *Visuospatial Sketchpad*

The VSSP is responsible for storing and processing visual and spatial information. It is composed of two components including the visual cache and the inner scribe. The visual cache passively stores information about form and colour whereas the inner scribe actively rehearses information stored in the visual cache and processes spatial information such as spatially perceiving the pitch of an auditory tone (Pratt, 1930; Hansen, Gonzalez, & Lyons, 2013) or remembering the spatial location of a target (Baddeley, 2003). A variety of tests have been developed to study visuospatial working memory including a picture span test (Tanabe & Osaka, 2009), a facial recognition task (Courtney, Ungerleider, Keil, & Haxby, 1996), and a Corsi block tapping task (CBTT; Corsi 1973). The CBTT, developed by Philip Corsi (1973), is one of the most widely used tests for studying the VSSP (Smyth & Scholey, 1994; Vandierendonck, Kemps, Fastame, & Szmalec, 2004; Vecchi & Richardson, 2001). It has been used to measure visuospatial working memory capacity in development and aging (Farrell Pagulayan et al., 2006; Park et al., 2002), in mental disorders such as obsessive-compulsive disorder (Zitterl et al., 2001), and in neurodegenerative diseases including Alzheimer's (Baudic et al., 2006) and Parkinson's (Stoffers, Berendse, Deijen, & Wolters, 2003). Furthermore, the CBTT has been widely used in experimental research to examine the deficits associated with acquired/traumatic brain injury (Kessels et al., 2000; Noe et al., 2005; Vallat-Azouvi, Weber, Legrand, & Azouvi, 2007). Despite its widespread use, the CBTT has many methodological inconsistencies including task administration (i.e., trials per level, physical vs. computerized versions), and scoring measures (i.e., block span, trial accuracy, target accuracy), which poses some limits on using CBTT to measure working memory capacity. In addition, some studies have examined how structural components (i.e., path configurations) of the CBTT affect working memory capacity (Busch, Farrell, Lisdahl-Medina, & Krikorian, 2005; Ginsberg, Rinehart, & Fielding, 2017; Orsini, Pasquadibisceglie, Picone, & Tortora, 2001; Orsini, Simonetta, & Marmorato, 2004; Parmentier, Elford, & Maybery 2005; Smirni, Villardita, & Zappala, 1983). Therefore, these methodological and theoretical limitations will be discussed in detail to provide a rationale for using the CBTT in the current thesis.

The traditional CBTT consists of an array of nine cubical blocks (3x3x3cm) situated on a table. The examiner taps a specific block sequence and instructs the participant to tap the exact sequence in the order of presentation. The sequence begins with two blocks and increases in difficulty up to a maximum of nine blocks to be recalled. Participants are given two attempts at each sequence length (i.e., the number of blocks to be remembered), otherwise referred to as level, set size or spatial span. The test is terminated if the participant fails to repeat both sequences at the same set size length and memory span (i.e., “spatial span”) is recorded as the highest sequence length successfully recalled. A review by Berch, Krokorian, and Huha (1998) examining 38 CBTT studies showed a lack of consistency in CBTT administration where experimenters often altered the block presentation and testing procedures such that there was inconstancy in the number of blocks, size or color of blocks, spatial location of blocks, and specific sequence configuration. The authors suggested that changing the number of blocks, block size or block placement might affect performance because the complexity of path configurations (i.e., distance between blocks, number of crosses) could increase or decrease task difficulty. Most of these studies did not report the path configurations used to investigate their hypothesis, thus a comparison between configurations could not be evaluated. However, research has since identified several key factors that can influence recall accuracy in addition to set size (i.e., # of blocks to remember): the number of path crossings (i.e., every time a sequence intersects itself), the path length (i.e., total distance of path) and the mean angle of block segments (i.e., the average of all the angles that are present in a sequence when connecting lines between consecutive blocks; Busch et al., 2005; Ginsberg et al., 2017; Orsini et al., 2001; Orsini et al., 2004; Parmentier et al., 2005; Smirni et al., 1983). As a result, the workload imposed by a sequence can vary depending on different path configuration characteristics or the number of items to be recalled (i.e., increase in set size).

Other differences in testing procedures outlined by Berch et al., (1998) included block tapping rate (i.e., 1, 1.5 or 3 sec/block), trials per set size (i.e., two, three, five or 10) and test termination criterion (i.e., 50% trials correct or >50% correct trials/span). Previous studies have not examined how tapping rate affects performance, however, we would expect that longer tapping rates would reduce performance because block locations would have to be held in working memory for a longer time risking the potential for memory decay. Similarly, guidelines for using an adequate number of trials per level have not been determined; however, it is likely that increasing the number of trials would provide a more reliable measure of working memory capacity. Lastly, Berch reported that 35 of 38 experimental studies had a test termination criterion where participants had to successfully recall 50% or greater trials per set size, which may improve scoring sensitivity because it reduces the effect of chance. Notably, one study by Smirni and colleagues (1983) had participants perform four trials at set sizes of three to nine regardless of failure at a particular length. They reported that 58% of participants correctly recalled a longer sequence while failing a shorter sequence. However, when controlling for path difficulty (i.e., group average performance on each sequence), only 6% of the participants successfully recalled a longer path after failing a shorter path. This may suggest that two trials per set size is not enough to reliably determine CBTT spatial span because administration characteristics, such as path configurations, have a significant effect on performance. Thus, standardizing the procedure of CBTT administration, such as shorter block-tapping rates (≤ 1 sec), increasing the number of trials per set size (3-5 trials), controlling for path configurations and assessing performance at all set sizes, may provide a more accurate measure of spatial working memory capacity.

Inconsistent scoring techniques have been also implemented in research studies that used the CBTT. Some scoring methodologies include spatial span (i.e., the longest block sequence correctly recalled), trial percentage (i.e., the mean percent of correct sequences recalled), target percentage (i.e., the percentage of targets correctly recalled) or a combination of the aforementioned methods. Importantly, these different scoring methodologies may affect the sensitivity of CBTT performance when comparing within or between groups. For instance, spatial span is considered one of the least sensitive measures because there is a limited range of scores (i.e., 2-9 blocks) and participants are only required to recall one sequence at each set size to achieve the highest score (Kessels et al., 2000). Furthermore, spatial span may not be sensitive to individual differences in performance because it does not account for the number of correct trials at each set size (Kessels et al., 2000). In contrast, trial percentage accounts for all trials improving its sensitivity and statistical reliability because the range of scores increases based on the number of trials at each set size. In addition, Farrell Pagulayan et al. (2006) found greater sensitivity in distinguishing between age groups using trial percentage compared to using a spatial span measure. To our knowledge no studies to date examined the sensitivity, validity or reliability of each scoring measure but one study reported greater sensitivity distinguishing between control participants and patients with cerebral lesions using a total score measure (i.e., the product of spatial span and trial percentage; Kessels et al., 2000) as compared to spatial span or trial percentage alone. Finally, studies that focused on target accuracy as a measure of CBTT performance (Conway et al., 2005; Friedman & Miyake, 2005; Redick et al., 2012) reported higher internal consistency compared to spatial span and trial percentage (Redick et al., 2012). Therefore, the current thesis will use target percentage as a scoring method to assess WM performance.

Many studies have been conducted to obtain normative data for the traditional CBTT (i.e., a board and blocks, two trials/level, 50% discontinuance criteria) across the lifespan (Kessels et al., 2000; Monaco, Costa, Caltagirone, & Carlesimo, 2013; Orsini et al., 1987; Farrell Pagulayan et al., 2006). These studies found that spatial span increases from childhood (5 ± 0.8 blocks at age 7) to adolescence (6.9 ± 1.1 blocks at 14 years), peaks in early adulthood (7.1 ± 1.0 blocks at 21 years; Farrell Pagulayan et al., 2006) and begins to decrease with each increasing decade of age (20 – 30 years = 6.00 blocks, 31 – 40 years = 5.94, 41 - 50 years = 5.50, 51 - 60 years = 5.56, 61 – 70 years = 5.17, 71 – 80 years = 5.02, 81 – 90 years = 4.42; Monaco et al., 2013). In addition, slight variations in mean spatial span performance have been reported in adult only populations. For instance, Kessels and colleagues (2000) reported a mean spatial span of 6.2 blocks in participants between the ages of 18-72 years (mean = 31.2 years) whereas other normative data studies (Monaco et al., 2013; Orsini et al., 1987; Farrell Pagulayan et al., 2006) showed a mean spatial span of 5.39 (ages 20-90 years), 4.55 (ages 20-99 years) and 7.1 (mean age 21 ± 4.5 years), respectively. This slight variation in performance may be due to several factors that were not controlled including average age, education level, and path configuration complexity or, this variation could represent normal variation in the population. In summary, CBTT normative data for the traditional design has shown a spatial span range of five to seven blocks for individuals aged 18-35 years.

Over the past two decades the CBTT has been modified to a computer-based version (eCorsi) that includes squares presented on a display which change colour and require the participants to reproduce the sequence by using a mouse or touch screen. The eCorsi version offers a distinct advantage in installation, set-up, and collection compared to the traditional CBTT because inter-stimulus intervals can be precisely set to eliminate examiner bias. Research has shown that computer-based versions produced similar mean spatial span performance when participants were separated into groups by age (Brunetti, Del Gatto, & Delogu, 2014; Nelson, Dickson, & Banos, 2000; Robinson & Brewer, 2016) compared to previous literature examining traditional CBTT performance in younger and older adults (Kessels et al., 2000; Orsini et al., 1987; Smyth & Scholey, 1994; Vandierendonck et al., 2004). For example, Brunetti and colleagues (2014) tested two age groups: 73 young adults (21.6 years ± 1.7) and 34 older adults (57.6 years ±1.7) using a tablet-based eCorsi platform (i.e., Apple iPad 2). Results showed younger and older adults mean spatial span of 6.1 ± 0.8 and 4.7 ± 1.2 blocks, respectively. Thus, eCorsi appears to provide a valid tool to measure visuospatial working memory.

Research focusing on the theoretical components of the CBTT using Baddeley's working memory model has suggested it relies on the VSSP slave system (Smyth & Scholey, 1994; Vandierendonck et al., 2004; Vecchi & Richardson, 2001) but requires support from the central executive at higher working memory loads (>4 blocks). For example, Smyth and Scholey (1994) performed five experiments where participants were presented with an eCorsi involving six trials at set sizes from three to seven. Between the block presentation and recall (i.e., maintenance phase) participants performed a secondary suppression task disrupting the phonological loop – continuously repeating the word 'de'(*articulatory suppression task)*, the visuospatial sketchpad - repeatedly tap four keys arranged in a square (*matrix tapping task*), or the central executive – tapping a random temporal pattern (*random-interval generation task*). The random-interval task is thought to disrupt the central executive because it places little load on either slave system thus requiring support from the central executive. Results showed a decline in spatial span for matrix-tapping (4.72 blocks) and random-interval generation (5.48 blocks) but no difference due to articulatory suppression (6.08 blocks) compared to single eCorsi performance (5.96 blocks). Further analyses showed that matrix-tapping (VSSP disruption task) reduced eCorsi performance at set sizes of 3-4, 5-6, and 7-8, whereas random-interval generation (central executive disruption) reduced eCorsi performance at spans 5-6 but not 7-8. The authors concluded that the eCorsi relies on the VSSP component of Baddeley's working memory model but receives additional support from the central executive when memory load exceeds four blocks. However, longer sequences (i.e., 7-8 blocks) may be too demanding on working memory so support from the central executive is not sufficient and performance declines. These results are analogous to findings from Vandierendonck et al., (2004) in the phonological domain showing deficits on a primary verbal task with secondary articulatory suppression or random interval generation tasks.

1.3.4 *Central Executive*

The central executive is described as the supervisory control system that coordinates the flow of information to and from the subsidiary slave systems (VSSP, PL, and episodic buffer) in Baddeley's model. It is responsible for focusing attention to a given task, dividing attention between two concurrent tasks, and binding information held in WM with long-term memories to create a more accurate perception of the current environment. Despite the criticism that the central executive is a vague component used to describe all functions not captured within the three slave systems, many studies have shown that the central executive can simultaneously carry out one task in each slave system without diminishing performance on either task (Collette & Van der Linden, 2002; D'esposito et al., 1995; Sala, Baddeley, Papagno, & Spinnler, 1995). For example, Sala and colleagues (1995) found that control participants could perform a verbal digit span task (i.e., phonological task) simultaneously with a box tracking task (i.e., VSSP task) without any performance deficits compared to performing each task alone. Interestingly, Sala showed that individuals with mild AD had performance decrements on both tasks in the dual condition despite no differences compared to controls in single task performance. This suggested a functional overlap in the neural networks responsible for the central executive and those affected by mildAD as well as the preservation of each slave system (VSSP, PL). It was hypothesized that the central executive system encompasses regions of the frontal lobe given the mild cortical atrophy seen in the AD group during pretest screening.

Multiple studies have focused on testing the central executive component in individuals with mTBI, including sports-related concussions (Bernstein, 2002; Howell et al., 2013, 2018; Fait, Swaine, Cantin, Leblond, & McFadyen, 2013; Parker et al., 2006; Tapper et al., 2017). These studies have reported significant deficits in the executive system in individuals with a history of concussion ranging from 30 days to eight years post-injury, despite being asymptomatic and cleared to return to play. For instance, research in our lab (Tapper et al., 2017) has shown that simultaneously performing an eCorsi task with a secondary auditory tone discrimination of pitch task results in a decrease in dual-task performance (i.e., auditory performance decrements) in individuals with and without a history of concussion. However, those with a history of concussion had a significantly larger deficit in auditory performance in the dual-task condition compared to controls. These findings suggest that both tasks rely on Baddeley's VSSP, and require support from the central executive, which appears to be impaired in those with a history of concussion.

Deficits in the central executive component following a concussion are hypothesized to result from a decrease in the availability of attentional capacity or poorer ability to appropriately allocate attentional resources at the cognitive stages of information processing (Bernstein, 2002; Register-Mihalik et al., 2013). In contrast, other research has suggested that these deficits arise because of problems filtering relevant from irrelevant information early in the sensory processing stream (Adams et al., 2020; Duncan et al., 2003, 2005; Gosselin et al., 2006; Ruiter et al., 2019; Tennant, 2018). One approach to testing whether sensory and/or cognitive processing is affected by a concussion is to measure ERPs while participants perform tasks that increase in workload. For instance, performing two tasks simultaneously where the primary task progressively increases in set size (i.e., number of blocks to remember) and the secondary task requires discrimination of relevant from irrelevant stimuli, can be used to determine whether deficits in behavioural performance are associated with changes in either sensory and/or cognitive processing stages. Importantly, this dual-task paradigm appears to be sensitive in distinguishing individuals with and without a history of concussion, thus, it may be a helpful to determine what mechanism(s) of information processing (i.e., sensory/cognitive processes) are disrupted in the chronic phase following a concussion.

1.4 Sensory stages of information processing

Sensory processing refers to the afferent transmission of sensory input from the receptors to the primary cortical sensory area (Kandel, 2013). *Sensory gating* refers to the brains ability to inhibit, suppress or filter sensory input to protect higher order cortical areas from being bombarded with irrelevant information (Cromwell, Mears, Wan, & Boutros, 2008; Grunwald et al., 2003). It has been widely studied using animal models (Bickford-Wimer et al., 1990; Braff & Geyer 1990) and human participants (Cromwell et al., 2008; Grunwald et al., 2003) across the three main sensory domains including vision (Adler, Waldo & Freedman, 1985; Duncan et al., 2005), somatosensation (Staines, Black, Graham, & McIlroy, 2002; Thoma et al., 2007), and audition (Jones, Hills, Dick, Jones, & Bright; 2016; Singhal, Doerfling, & Fowler, 2002). Additionally, sensory gating has been examined in aging (Gmehlin, Kreisel, Bachmann, Weisbrod, & Thomas, 2011; Lijffijt et al., 2009a), concussion (Adams et al., 2020; Duncan et al., 2003, 2005; Gosselin et al., 2006), and schizophrenia (Thoma et al., 2007) to identify the brain structures and mechanisms mediating the gating process and how it is affected by neurological disorders. Sensory gating can be tested using event-related potentials (ERP) collected during the performance of a selective attention task such as the oddball paradigm, where participants respond to a relevant stimulus while ignoring an irrelevant stimulus. ERP amplitudes elicited by relevant stimuli can be compared to amplitudes elicited by irrelevant stimuli at the sensory stages of information processing (i.e., 50-250ms). In the auditory domain, the P50 (15-80ms post stimulus) and N100 (80-170ms) are categorized as sensory responses and hypothesized to reflect early and late sensory gating mechanisms, respectively (Joos et al., 2014; Grunwald et al., 2003; Sur & Sinha, 2009). It has been suggested that these two ERPs (P50, N100) represent exogenous (i.e., bottom-up) processes that receive little input from higher order areas; however, observations indicate that they can be mediated by endogenous (i.e., top-down) attentional processes (Joos et al., 2014).

1.4.1 Bottom-up vs. Top-down Sensory Gating Pathways

There is continued debate as to whether sensory gating reflects a bottom-up (involuntary, automatic, pre-attentive) or a top-down (voluntary, attentive) process that functions to protect higher-order areas from being bombarded with irrelevant information. Evidence supporting bottom-up auditory gating has shown that the dorsal nucleus of the lateral lemniscus (i.e., brainstem area) sends GABAergic projections to the central nucleus of the inferior colliculus to inhibit startling or reflective sounds (i.e., an echo) in less than 50 ms (see review by Li & Yue, 2002). This automatic gating mechanism has been shown to occur in rats with the cerebral cortex removed (Li & Frost, 2000) indicating a bottom-up, non-selective sensory gating mechanism occurring without voluntary control. In contrast, other research has supported top-down sensory gating showing that the prefrontal cortex can facilitate processing of relevant information and/or inhibition of irrelevant stimuli (Knight et al., 1999; Sherman & Guillery, 2002; see review by Bartlett, 2013) through multiple connections including cortico-reticular-thalamic, cortico-thalamic or cortico-cortical (Barry, Robertson, & Mulders, 2017).

The top-down sensory gating process may occur through the thalamic reticular nucleus (TRN), an inhibitory sheath mainly composed of GABAergic neurons (Knight et al., 1999; Zikopoulous & Barbas, 2006), which acts as a “gatekeeper” to facilitate or attenuate sensory information from reaching the primary auditory cortex. The TRN receives monosynaptic glutamatergic inputs from the cerebral cortex, which can either excite the TRN causing sensory inhibition or excite the surrounding areas causing a lateral inhibition effect resulting in the enhancement of relevant information (Pinault, 2004). An alternative indirect pathway involves the nucleus accumbens (Barry, Paolini, Roberston, & Mulders, 2015; Barry et al., 2017), which receives direct connections from the ventromedial and dorsolateral PFC, and appears to have direct excitatory connections to the TRN (inhibitory effect) or indirect connections to the basal ganglia (disinhibitory effect; O'Donnell, Lavin, Enquist, Grace, & Card, 1997). Studies using a murine model (Barry et al., 2015, 2017) have shown that stimulating the nucleus accumbens results in decreased activity of medial geniculate body (MGB) neurons at mid latencies (~50 ms post-stim) compared to the stimulation of the medial PFC (~30 ms post-stim; homologous to human DLPFC and ventromedial PFC), which suggests that the medial PFC activates an earlier gating mechanism. Lastly, the PFC (i.e., frontopolar, lateral prefrontal cortex) predominately innervates excitatory neurons in the auditory cortex (Kauramäki, Jääskeläinen, & Sams, 2007; Medalla & Barbs, 2014; Petkov et al., 2004), which can act to enhance relevant information (Stuss & Knight, 2013); in contrast, the PFC only innervates approximately 20% of inhibitory neurons in the auditory cortex. The attentional modulation of relevant information in the auditory cortex has been consistently shown in human studies involving fMRI and ERPs (Ahvenin et al., 2006; Kauramaki et al., 2007; Petkov et al., 2004; Woldorff et al., 1993; Woldorff & Hillyard, 1991). This gating mechanism seems to occur within 80-170ms in the auditory cortex. In summary, research in animals and humans supports three top-down pathways involved in auditory sensory gating including cortical-TRN-thalamic (~30ms), cortical-NA-TRN-thalamic (40-80ms), or cortico-cortical (80-170ms).

1.5 Sensory event-related potentials

One-way to gain more insight into sensory gating in humans is to use EEG to record sensory ERPs that occur within specific time-frames (e.g., 40-80ms, 80-170ms) at different brain locations (e.g., frontal, parietal, temporal).

1.5.1 P50 Potential

The P50 ERP waveform, also known as the P1 or Pb complex, is a positive evoked auditory potential peaking around 40-80 ms over the frontal-central electrodes (Fz, Cz). It has been proposed that the P50 amplitude reflects an early, preattentive sensory gating mechanism where redundant or irrelevant auditory information is automatically inhibited without the direction of attention (Jones et al., 2016; Korzyukov et al., 2007). The most widely used paradigm to study the P50 gating mechanism is the paired-click paradigm where participants passively listen to two identical auditory stimuli with an inter-stimulus interval less than one second (usually ~500ms). When the S2 is presented within 500 ms of S1, the P50 amplitude for S2 is reduced by 30-80% in healthy participants (Dalecki, Croft, & Johnstone, 2011), and this reduction is inversely related to the inter-stimulus interval (ISI) duration (Dolu, Suer, & Ozesmi, 2001). The potential mechanism responsible for causing the ISI effect is not fully understood; however, Dolu et al., (2001) proposed that sensory inhibition is maximal when stimuli are presented approximately 500ms apart to limit the formation of associations with other irrelevant sensory features.

Research on the neural mechanism responsible for the P50 gating phenomenon has suggested that the neural generators are localized in the frontal and temporal lobes (Grunwald et al., 2003; Jones et al., 2016; Korzyukov et al., 2007). For instance, Korzyukov and colleagues (2007) studied nine epileptic participants using the paired-click paradigm with embedded intracranial electrodes placed on frontal and temporal lobe areas. Results showed a significant reduction in amplitude (i.e., >30%) between S1 and S2. Source localization methods identified temporal lobe (temporoparietal junction, superior temporal gyrus) and frontal lobe (DLPFC, premotor & supplementary motor cortex, anterior cingulate cortex) areas contributing to auditory sensory gating. These findings suggest a top-down frontal network that is important for mediating the gating response, which is inconsistent with the view that P50 reflects a "preattentive" mechanism that occurs automatically due to the neural excitation of a set of neurons for S1 and the simultaneous activation of a second set of inhibitory neurons reducing S2 (Anokhin et al., 2007). Other studies using surface EEG at electrodes FCz and Cz in healthy (Jones et al., 2016; Weisser et al., 2001) and disease or injured populations (Knight et al., 1999; Korzyukov et al., 2007; Williams, Nuechterlein, Subotnik, & Yee, 2011) have reported a similar contribution of frontal networks to the gating response. Thus, the P50 ERP may reflect an interaction between top-down and bottom-up influences. Importantly, disease or injured populations (i.e., Schizophrenia, TBI) do not exhibit a difference in the P50 amplitudes between the two stimuli, suggesting a deficit in the neural circuitry involved in sensory gating. For example, Knight and colleagues (1999) found no difference in P50 ERP amplitude between S1 and S2 in patients with a DLPFC lesion. In summary, results from paired-click paradigm studies suggest that the P50 ERP amplitude reflects a preattentive sensory gating mechanism that is mainly localized in the temporal lobe but is can be mediated by top-down attentional control from the frontal lobe by selecting relevant from irrelevant stimuli based on task instructions.

Another paradigm used to investigate sensory gating is the auditory oddball task, which requires participants to make a simple response (i.e., key touch or mouse click) to a relevant target tone while withholding a response to an irrelevant non-target tone. Mixed results have been reported when studying the P50 ERP amplitude during the auditory oddball task (Boutros et al., 1995; Ermutlu, Demiralp, & Karamursel, 2007; Oades, Zerbin, & Dittmann-Balcar, 1995; Sambeth et al., 2003). Some research has shown larger P50 ERP amplitude to target auditory tones compared to non-target tones (Boutros et al., 1995; Oades et al., 1995), whereas others report no amplitude difference between tone types (Ermultu et al., 2007; Sambeth et al., 2003). The opposing findings could be attributed to methodological differences in interstimulus interval (ISI) duration as sensory gating differences were present in studies with shorter ISIs (<2s) and absent in studies with longer ISIs (>3s). One exception was reported by Ermultu and colleagues (2007) who showed sensory gating was optimal at a 2.5s ISI and thought this was due to the oscillatory nature of the brainstem, which rhythmically discharges cholinergic neurotransmitters causing a larger gating-in of target stimuli. Notably, Ermutlu did not show amplitude differences between tones at a 1.5s ISI contrasting early findings by Boutros (1995) and Oades (1995). Despite mixed results, research supports that sensory gating occurs in the oddball task at an early, sensory stage (i.e., 40-80ms post-stimulus) and that the effect is modulated by ISI.

1.5.2 N100 Potential

The N100 is a sensory auditory evoked potential occurring between 80-170ms post stimulus onset. It is thought to reflect a later, attention driven stage of the sensory gating process that is subserved by overlapping brain areas also contributing to the generation of the P50 ERP. In addition, source localization studies have identified other areas contributing to the generation of the N100 including hippocampal, cingulate and thalamic regions (Boutros et al., 1999;

Boutros, Gjini, Urbach, & Pflieger, 2011; Grunwald et al., 2003; Pantev et al., 1988; Scherg, Wajsar, & Picton, 1989). Research studying the N100 has used similar paradigms that were used to study the P50 ERP such as a paired click paradigm or an auditory oddball task. These studies suggest that the N100 may be an indicator of a selection process used to gate in relevant input (Boutros, Belger, Campbell, D'Souza, and Krystal, 1999; Lijffijt et al., 2009; Näätänen & Picton, 1987; Riccio, Reynolds, Lowe, & Moore, 2002; Sklar & Nixon, 2014). In support, recent research has shown that the N100 ERP amplitude can be modulated by the behavioural state of the participant based on the instructions to attend to or disregard a stimulus, which suggests that this later sensory ERP has an important role in gating sensory information (Lijffijt et al., 2009; Riccio et al., 2002; Yurgil & Golob, 2013). Similar to the P50, the N100 ERP amplitude magnitude and gating difference (target – non-target) are affected by the ISI duration with shorter ISIs (i.e., $\leq$1.5s) resulting in smaller target and non-target amplitudes (Ermutlu et al., 2007; Pereira et al., 2014) but a larger sensory gating difference between target and non-target amplitudes (Anderer et al., 1998; Ermutlu et al., 2007). In contrast, longer ISIs ($\geq$ 2.5s) have larger target and non-target N100 amplitudes (Ermutlu et al., 2007; Pereira et al., 2014) and a smaller sensory gating difference (Ermutlu et al., 2007; Sambeth et al., 2003). Näätänen and Picton (1987) proposed this gating effect might be only present during shorter ISIs because the neural memory trace of the non-target stimulus decays with longer ISIs, thereby reducing the ability to compare target to non-target stimuli. In summary, the P50 ERP might reflect an exogenous cortical potential (i.e., preattentive) responsible for gating out irrelevant information but it can be influenced by top-down attentional processes. The N100 might also reflect an exogenous cortical potential that can be influenced by top-down attentional processes; however, it reflects the gating in of relevant information. Importantly, both ERPs (P50, N100) might change depedening on the paradigm used (passive paired click vs. oddball) and task instructions given (i.e., ignore a tone or respond to a tone).

1.6 Cognitive stages of information processing

Cognitive processing refers to a later processing stage (i.e., higher level processing) where sensory input can be combined with information stored in long-term memory to guide decisions or to make a motor response. Cognitive stages of information processing can be investigated using ERPs that occur later, such as the P300 ERP, which is elicited by the visual or auditory oddball task. In the auditory domain, the amplitude of P300 ERP is hypothesized to reflect the amount of attentional resources available, the allocation of attentional resources towards a stimulus requiring a response, or the updating of contextual information in working memory at the cognitive stage of information processing (Grunwald et al., 2003; Sur & Sinha, 2009). The brain structures involved in cognitive processing stages are subserved by areas localized in the frontal and parietal lobes including prefrontal cortex, the temporal-parietal junction, and primary auditory cortex (Brazdil et al., 2005).

The P300 ERP is a positive waveform distributed over the midline electrodes Fz, Cz and Pz. This late-latency potential reflects a top-down or voluntary control mechanism (Başar, Başar-Eroglu, Rosen, & Schütt 1984; Debener, Kranczioch, Herrman, & Engel, 2002; Sur & Sinha, 2009; Watter, Geffen, & Geffen, 2001) related to the brain's capacity to process a task relevant stimulus embedded amongst distractors (Frodl-Bauch, Bottlender, & Hegerl, 1999). The P300 ERP is quantified using the amplitude and latency measured from stimulus-onset to the most positive amplitude peak between 250-500ms. The P300 ERP consists of two positive peaks including the P3a, a large positive deflection with a fronto-central distribution and the P3b, a smaller positive deflection with a centro-parietal distribution and longer latency than the P3a (Frodl-Bauch et al., 1999; Linden, 2005; Soltani & Knight, 2000; Wronka, Kaiser, & Coenen, 2012). The P3a is elicited using a rare, *novel* stimulus in the three-stimulus oddball paradigm (*novel*, target, and non-target) suggesting it reflects an alerting process to an unexpected stimulus with neural generators in the lateral and medial frontal cortex (Wronka et al., 2012). The P3b deflection results from an infrequent "target" stimulus embedded within frequent "non-target" standard stimuli in either a two-stimulus or a three-stimulus oddball paradigm. Its generator is localized in the parietal lobe (superior parietal lobule, inferior parietal lobule, postcentral gyrus, posterior cingulate gyrus).

Research has shown that the P300 amplitude and latency are influenced by stimulus probability and task difficulty (Johnson & Donchin, 1982; Polich, 1987; Squires, Wickens, Squires, & Donchin, 1976). Stimulus probability is defined as the percentage of target tones embedded within a stream of standard non-target tones (i.e., distractors). Stimulus probability was first studied by Johnson and Donchin (1982) who found larger P300 amplitudes and longer latencies to target stimuli in the two-stimulus oddball task when the probability of a target was set at 33% compared to 67%. Task difficulty can be manipulated by changing the discriminability between target and non-target tones (i.e., tone intensity in decibels) or by performing two tasks simultaneously (i.e., dual-tasking). For example, Polich (1987) studied the effect of task difficulty (stimulus discriminability) and stimulus probability on P300 amplitude and latency. They found that P300 amplitude decreased when target discriminability difficulty increased from easy (40dB non-target; 60dB target) to hard (40dB non-target, 45dB target*)*, and as target probability increased (10% to 30%). In addition, P300 latency was longer in the hard compared to easy condition, and this latency became shorter as target probability increased.

These results are consistent with the hypothesis that the P300 ERP component reflects an attentional mechanism because more difficult tasks (i.e., lower tone discriminability) thought to consume more attentional resources result in a decreased P300 amplitude and increased latency. In contrast, easy task situations requiring few attentional resources are associated with larger P300 amplitudes and shorter latencies.

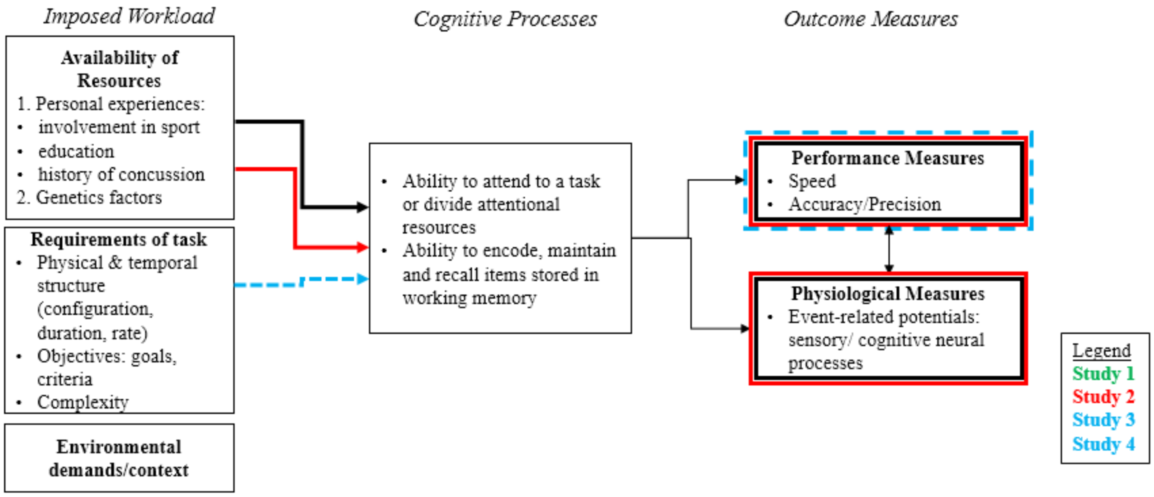
The P300 potential is also influenced when participants perform two tasks simultaneously (dual-tasking/divided attention). Several studies investigated the P300 amplitude and latency in single and dual-tasks to understand its response to changes in mental workload (Singhal et al., 2002; Singhal & Fowler, 2004; Watter et al., 2001). For instance, Singhal et al., (2002) examined task difficulty using four different conditions including a single dichotomous listening task (respond to infrequent target tones and ignore frequent non-target tones), a single aircraft landing task with two levels of difficulty (low and high turbulence), an easy dual-task (low turbulence + dichotomous listening task), and a hard dual-task (high turbulence + dichotomous listening task). Results showed a decrease in P300 amplitude and increase in P300 latency with increased task difficulty at electrode Pz. No significant results were shown at electrode Cz, however, it did follow the same trend. Behavioural performance on the auditory task showed a decrease in accuracy and increase in response time as task difficulty increased (auditory single → dual easy → dual hard). Aircraft landing performance decreased from low to high turbulence but not between task conditions (single, dual). These findings suggest that as workload increases, there are fewer attentional resources available or participants struggle to appropriately allocate attentional resources to perform the secondary auditory task, which is reflected in a decreased P300 amplitude and increased latency. Similar ERP results were reported by Singhal and Fowler (2004), who asked participants to perform a working memory task simultaneously with a dichotomous listening task. The memory task involved temporarily storing five digits before being probed with a digit that was either included or excluded from the set. They found smaller P300 amplitude in the dual-task condition compared to the single-task at electrodes Cz and Pz, and longer latencies at electrode Pz. The authors suggested that the P300 differences occurring between single and dual tasks reflected an attentional capacity driven mechanism that becomes consumed when performing a challenging primary memory task. The studies provided valuable insight into the effects of increased workload on cognitive stages of information processing. However, most of these dual-task studies involve a dichotomous approach to mental workload (i.e., single-task vs. dual-task); thus, we do not know how progressive increases in mental workload affect information processing. One approach to study this question is to progressively increase the number of items to be remembered (i.e., working memory) while simultaneously performing a secondary auditory oddball task. This is important because understanding how cognitive stages of information processing (i.e., P300 ERP) are affected by progressive increases in mental workload in individuals with no history of concussion might provide insight into what neural mechanism is contributing to the persisting subtle behavioural deficits in individuals with a history of concussion.

1.8 Mental Workload Framework

The overarching goal of this thesis is to investigate the behavioural and electrophysiological mechanisms of mental workload in individuals with and without a history of concussion. The specific goals and objectives are captured in the mental workload framework depicted in Figure 1.1. In the literature, mental workload has been used interchangeably with terms such as cognitive load, attentional load or working memory load (Brouwer et al., 2012) to describe the relationship between the cognitive demands imposed by a task and the availability of cognitive resources to perform the task (Kahneman, 1973; Wickens, 2002; Xie & Salvendy, 2000). In our framework, mental workload is defined as the effort required by an individual to achieve a certain level of performance and emerges from the interaction between the *availability of resources* – which can be influenced by personal experiences (e.g., education, involvement in sport, history of concussion) and genetics, the *requirements of a task* – the physical and temporal structure of the task (e.g., configuration, duration, type, complexity), and the *environmental context* – where the task is being performed (quiet vs. busy setting). The imposed workload affects an individual's cognitive processes such as their ability to attend to a task or divide attention between tasks, and the ability to encode, maintain and recall items stored in working memory. Outcome measures such as behavioural performance (i.e., task accuracy and response time), and physiological responses (i.e., sensory and cognitive neural processes) can be used to quantify the effect of the imposed workload.

Figure 1.1

Mental workload framework summarizing the work presented in this thesis



1.9 Research Questions and Hypotheses

In this thesis, studies one and two examined mental workload by using behavioural performance and ERP measures to assess the availability or allocation of resources in team sport athletes with and without a history of concussion while they performed a dual-task paradigm that relied on the VSSP and central executive components of Baddeley's WM model (i.e., eCorsi and auditory oddball task; see Figure 1.1). Mental workload was manipulated at two levels including eCorsi set size (i.e., # of items to be remembered) and by performing both tasks simultaneously (i.e., dual-task/divided attention) compared to alone. The third and fourth study aimed to examine how changing the requirements of the eCorsi task (i.e., pattern configuration) influences mental workload. In particular, study three investigated how changing the average angle of a pattern influences target recall accuracy when the task is performed alone. The purpose of this study was to gain a better understanding of the factors that influence mental workload. Study four aimed to build on study three by examining whether more difficult sequences within a set size (i.e., # of blocks presented) influence secondary auditory oddball task performance.

Study 1 Research Question:

What is the effect of increased mental workload on early sensory gating assessed using the P50 and N100 ERP components, and later stages of cognitive processing assessed using the P300 ERP component?

Hypothesis 1: Increases in mental workload (i.e., set size and single/dual) will be associated with reduced amplitude of the P50 and N100 ERPs, which reflect early sensory and late sensory stages of information processing. In particular, P50 & N100 sensory gating will decrease as a *function of mental workload because fewer resources will be available to inhibit irrelevant information (i.e., P50) and facilitate relevant information (i.e., N100).*

Hypothesis 2: As workload increases (single to dual-task), the effect on the cognitive stage will be a reduction in P300 ERP amplitude because attentional resources are consumed by the primary working memory task.

Study 2 Research Question: What is the effect of concussion on sensory gating and later stages of cognitive processing as a function of mental workload?

Hypothesis 1: Those with a history of concussion will have a reduced amplitude of the P50 and N100 ERPs compared to those without a history of concussion, and these ERPs will decrease as a function of mental workload because concussions cause damage to the frontal networks involved in sensory processing. In addition, sensory gating will be poorer in those with a history of concussion (P50 & N100) as a function of mental workload because these individuals will have to dedicate more resources to maintain primary task performance leaving fewer resources to accurately differentiate relevant from irrelevant information on the secondary task.

Hypothesis 2: Those with a history of concussion will have a reduced P300 amplitude compared to the non-concussion group and this reduction will further decrease as a function of mental workload.

Study 3 Research Question:

Do path configurations with more acute angles increase the mental workload of the eCorsi task?

Hypothesis: Mental workload will be higher for path configurations that have more acute angles, which will be associated with poorer recall accuracy.

Study 4: **Research Question:**

What is the effect of eCorsi pattern workload on secondary auditory oddball task performance?

Hypothesis: Oddball task performance will decrease as a function of eCorsi task difficulty (i.e., increase in set size & path configuration characteristics) because more attentional resources will be used to encode the sequence.

Section 2 - *Effects of progressively increased mental workload on early and late auditory event related potentials in athletes*

2.1 INTRODUCTION

Everyday humans interact in challenging environments that require us to prioritize certain information while disregarding other. As task demands or environment complexity increase, the neural resources used to prioritize important information become depleted, resulting in deteriorated behavioural performance, for example, reduced accuracy and longer response times. Understanding the neural mechanism(s) that underlie efficient allocation of neural resources with increasing mental workload has become a key area of interest in neuropsychological research. In particular, this research has implications for a wide range of life skills including occupational performance, athletic skills, and driving ability. In addition, studying how the brain responds to mental workload in healthy individuals can help guide future research into understanding the brain's limitations following neurodegenerative disorders (i.e., Alzheimer's disease, dementia, Parkinson's disease) or acquired brain injury (i.e., stroke, traumatic brain injury).

The term "mental workload" has been used to characterize the effort required by an individual to achieve a certain level of performance (Hancock & Meshkati, 1988), which is dependent on the availability of neural resources, requirements of a task, and environmental demands/context (Wickens, Hollands, Banbury, & Parasurman, 2015). An influential study by Wickens, Isreal and Donchin (1977) revealed that event-related potentials (ERPs) can be used to quantify the neural correlates of mental workload. ERPs are recorded using electroencephalography and measure small electrical signals produced by the brain in response to a specific sensory, cognitive, or motor event (Sur & Sinha, 2009). Wickens et al., (1977) found that the P300 complex amplitude, an ERP elicited over central-parietal sites 250-500ms following an infrequent (i.e., oddball) auditory stimulus, decreased when participants were presented with a discrete auditory stimulus while simultaneously performing a visual tracking task compared to when the auditory stimulus was presented alone. This seminal study led to a fruitful line of research that adopted a dual-task paradigm approach to further understand how mental workload affects cognitive ERPs, in particular, the amplitude of the P300 potential (Isreal, Chesney, Wickens, & Donchin, 1980; Kasper, Cecotti, Touryan, Eckstein, & Giesbrecht, 2014; Kramer, Wickens, & Donchin, 1985; Parasuraman, 1985; Polich, 1987; Singhal, Doerfling, & Fowler, 2002; Wester, Böcker, Volkerts, Verster, & Kenemans, 2008). Subsequent dual-task studies have revealed an inverse relationship between P300 amplitude and the difficulty of the primary task (Isreal et al., 1980), supporting the notion that the cognitive process reflected by the P300 is the allocation of attentional resources (Kahneman, 1973; Kasper et al., 2014; Parasuraman, 1985; Polich, 2007; Singhal et al., 2002; Solis-Marcos & Kircher, 2019; Ullsperger, Freude, & Erdmann, 2001; Watter, Geffen & Geffen, 2001; Wickens, 2002). However, there is continued debate that the P300 might reflect other cognitive processes, such as decision making (O'Connell, Dockree, & Kelly, 2012), stimulus-response link (Verleger, Baur, Metzner, & Smigasiewicz, 2014) or updating of working memory (Gevins & Smith, 2000).

More recent research revealed that sensory ERPs are important indicators of how the central nervous system (CNS) prioritizes information during the performance of sensorimotor (Adams, Popovich, & Staines, 2017; Peters et al., 2019; Staines, Graham, Black, & McIlroy, 2002) and cognitive (Kasper et al., 2014; Singhal et al., 2002) tasks in order to protect higher order cognitive processes from being bombarded with irrelevant sensory information (Boutros, 1995; Boutros, Belger, Campbell, D'Souza, and Krystal, 1999; Ermutlu, Demiralp, & Karamursel, 2007; Knight et al., 1999). Notably, results from studies using visual-auditory dual-tasks have shown that the N100 component typically decreases in amplitude when performing two tasks simultaneously suggesting that later, sensory ERPs are also influenced by mental workload (Kasper et al., 2014; Parasuraman, 1985; Singhal et al., 2002, 2004; Solis-Marco & Kircher, 2019; Ullsperger et al., 2001). In contrast, dual-task studies examining the amplitude of earlier, sensory ERPs, such as the P50 component, have shown mixed results with the introduction of a secondary task (Kho et al., 2003; Paleske, 2019; White & Yee, 1997; Yee & White, 2001). These findings indicate that the P50 and N100 ERPs may reflect different stages of sensory processing. Therefore, it is important to understand the effects of mental workload on sensory ERPs because they may reflect different mechanisms that could in turn influence the efficacy of later cognitive processing. In particular, efficient sensory processing could serve to protect higher order cognitive processes from being overloaded with irrelevant sensory information.

The P50 and N100 auditory ERPs occur 40 to 80 ms and 80 to 170 ms post stimulus, respectively. Both potentials have the largest amplitude over frontal-central electrodes, suggesting the neural generators are mainly localized in the frontal and temporal lobes (Grunwald et al., 2003; Knight et al., 1999; Korzyukov et al., 2007; Näätänen & Picton, 1987; Whittingstall, Stroink, & Dick, 2004; Weisser et al., 2001). However, source localization studies have identified potential contributions from medial temporal lobe, cingulate and thalamic regions (Boutros, Gjini, Urbach, & Pflieger, 2011; Grunwald et al., 2003). Numerous studies have examined auditory sensory ERPs using a paired click paradigm, where participants were instructed to passively listen to two click pairs (Dalecki, Croft, & Johnstone, 2011; Dolu, Suer, & Ozesmi, 2001; Jerger, Biggins, & Fein, 1992; Lijffijt et al., 2009a, 2009b; Rentzsch, Jockers-Scherübl, Boutros, & Gallinat, 2008; Wan, Friedman, Boutros, & Crawford, 2008). When the second stimulus (S2) is presented within 500ms of the first stimulus (S1), both P50 and N100 amplitudes following S2 are significantly reduced by 30-80% in healthy subjects (Dalecki et al., 2011; Dolu et al., 2001). These findings suggest that the P50 and N100 ERPs reflect neural activation in the cortical areas that gate out redundant sensory information or the influence of other cortical areas on the gating process (i.e., frontal areas). Additional studies using the paired click paradigm have proposed that these sensory ERPs reflect a multistage sensory gating processes where the amplitude of the P50 is an indicator of an early, preattentive inhibitory mechanism responsible for gating out irrelevant/redundant information (Jerger et al., 1992; Grunwald et al., 2003; Knight et al., 1999; Wan et al., 2008), and the amplitude of the N100 ERP is an indicator of a later, attentive phase responsible for gating-in relevant input (Boutros et al., 1999; Sklar & Nixon, 2014).

Another paradigm that has been used to investigate early (P50) and late (N100) sensory ERPs is the auditory oddball task, which requires participants to make a simple response (i.e., key touch or a mouse click) to a relevant target tone while withholding a response to an irrelevant non-target tone. Similar to the paired click paradigm, these sensory ERPs are thought to reflect different stages of sensory gating. However, a broader definition of sensory gating has been used in the oddball task, which encompasses the brain’s ability to modulate incoming information by either facilitating or attenuating the magnitude of a cortical response to relevant and irrelevant stimuli, respectively (Braff & Geyer, 1990). Previous research using the oddball task has shown that P50 and N100 ERP amplitudes can be modulated by the behavioural state of the participant based on the instructions to attend to or disregard a stimulus. As a result, these sensory ERPs appear to reflect the gating in and/or gating out of sensory information (Anderer Pascual-Marqui, Semlitsch, & Saletu, 1998; Boutros et al., 1995; Ermutlu et al., 2007; Oades, Zerbin, & Dittmann-Balcar, 1995; Riccio, Reynolds, Lowe, & Moore, 2002; Sambeth et al., 2003). Importantly, this sensory gating mechanism is only present at short (<2s; Anderer et al., 1998; Boutros et al., 1995; Ermutlu et al., 2007; Oades et al., 1995) but not long (>2.5s; Ermultu et al., 2007; Sambeth et al., 2003) interstimulus intervals (ISI) because the neural memory trace of the non-target stimulus decays with longer ISIs, reducing the ability to compare target to non-target stimuli (Näätänen and Picton, 1987). Based on the findings from auditory oddball studies, it has been proposed that the amplitude of the P50 and N100 ERPs reflects sensory gating mechanisms that are mediated by overlapping areas localized in the frontal lobe but might have distinct roles to gate-out (P50) and gate-in (N100) sensory input (Boutros et al., 1995; Ermutlu et al., 2007; Oades et al., 1995; Yurgil & Golob, 2014).

Several studies have used a dual-task paradigm to investigate the amplitude of sensory ERPs as a function of mental workload (Harmony et al., 2000; Kasper et al., 2014; Paleske, 2019; Miller, Rietschel, McDonald, & Hatfield, 2011; Parasuraman, 1985; Singhal et al., 2002, 2004; Solis-Marco & Kircher, 2019; Ullsperger et al., 2001; White & Yee, 1997; Yee & White, 2001). Dual task paradigms offer additional insight into the role of sensory gating because they provide a more comprehensive view of how sensory information is prioritized when increases in mental workload consume attentional resources. Research has shown that the auditory N100 ERP amplitude progressively decreases as the amount of attentional resources directed towards the visual domain increases when performing a continuous audiovisual dual-task presented at short ISIs (400-800ms) but not at long ISIs (1000-1400ms) (Parasuraman, 1985). Corroborating research has shown reduced N100 ERP amplitude when subjects simultaneously perform a primary task (e.g., mental arithmetic, gauge monitoring, simulated driving or flying, or visual tracking) with an auditory oddball task compared to performing the auditory task alone (Kasper et al., 2014; Singhal et al., 2002; Solis-Marco & Kircher, 2019; Ullsperger et al., 2001). Notably, Ullsperger and colleagues (2001) showed decreases in N100 ERP amplitude for both target and non-target tones when subjects performed a mental arithmetic task or gauge monitor task simultaneously with the auditory oddball task compared to performing the oddball task alone. In addition, both target and non-target tone amplitudes further decreased when all three tasks were performed together suggesting that the N100 is affected by the attentional resource depletion when mental workload increases; however, the authors did not report any differences between target and non-target tone amplitudes (i.e., gating difference) as a function of workload.

To our knowledge, no research has investigated the P50 ERP response to mental workload using an auditory oddball task. This is fundamentally important because it could help to establish a distinct contribution of each stage of sensory processing (i.e., early versus late). For instance, if P50 amplitude does not change as a function of mental workload then it would suggest that this ERP reflects an early, “preattentive” sensory process that is unaffected by the diminished attentional resources resulting from increased workloads (i.e., dual-task versus single-task). Only few studies have investigated the P50 ERP response as a function of mental workload when subjects passively listened to a paired-click paradigm while performing a visual match-to-sample task (Paleske, 2019), a silent counting task or silently solving mental arithmetic problems (White & Yee, 1997; Yee & White, 2001) or, a reversed digit-span task (Kho et al., 2003) compared to listening to the clicks alone. Results showed no difference in the P50 amplitude magnitude following the first and second clicks, and no gating difference (i.e., second click subtracted from first click) when tasks were performed simultaneously compared to alone. In contrast, White & Yee (1997, 2001) showed that the P50 ERP amplitude associated with the first auditory click (i.e., a relevant sensory stimulus) was reduced when subjects simultaneously passively listened to the paired-click paradigm with an auditory recording of a voice counting or when they solved mental arithmetic problems aloud. The authors suggested that the smaller P50 amplitude was due to the higher demands of the mental arithmetic task (i.e., silent versus oral) or the competing auditory stimulation of their own voice. Therefore, the P50 may not reflect a strictly early, “preattentive” inhibitory sensory processes, rather it may also serve to gate-in relevant sensory information, which can be influenced by the degree of mental workload such that high workloads consuming more attentional resources result in reduced facilitation of relevant information.

The objective of this study was to advance our understanding of the neural correlates of mental workload by examining ERPs that reflect multistage attentional processes using a novel dual-task paradigm that progressively increases in difficulty. Previous studies examining mental workload have instructed subjects to perform a continuous task such as visual detection (Kasper et al., 2014), flight or driving simulation (Baldwin & Coyne, 2005; Singhal et al., 2002, 2004; Solis-Marcos & Kircher, 2019), or mental operations/arithmetic (Ullsperger et al., 2001) simultaneously with the auditory oddball task. One limitation associated with these experimental designs is that it is difficult to quantify the mental workload of the primary task. For example, a visual object may change in orientation making it easier or harder to detect, a flight/driving navigation pattern may alter its path making it more difficult to keep the vehicle within the instructed path/lane, or the arithmetic problem may require more mental resources to solve. A second limitation is that these studies have typically taken a binary approach by comparing single to dual-task conditions, which does not provide insight about the effects of progressive increases in mental workload on ERPs. Lastly, most mental workload studies have focused on the later, cognitive stages of information processing, therefore, our understanding of the effects of workload on sensory ERPs, such as the P50 or N100 is limited. For instance, studies examining sensory ERPs have analyzed target and non-target amplitudes separately; thus, we do not know how sensory gating (i.e., difference in amplitude between targets and non-targets) is affected by mental workload. To address these limitations, our task was designed to precisely manipulate mental workload by varying set size (# of items to be remembered) and task condition (single, dual). In addition, we investigated how both sensory and cognitive ERPs change as a function of mental workload. In particular, we examined the ERP amplitudes for target and non-target auditory stimuli and the gating difference at the sensory stages of information processing (i.e., P50, N100). We hypothesized that P50 & N100 sensory gating will decrease as a function of mental workload because fewer attentional resources will be available to inhibit irrelevant sensory information and/or facilitate relevant information. We also hypothesized that the P300 amplitude will decrease as a function of mental workload because fewer attentional resources will be available at the cognitive stages of information processing.

2.2 METHODS

2.2.1 Participants

Twenty graduate and undergraduate students who participated in one or multiple varsity or competitive recreational sports (soccer, hockey, basketball, rugby, ultimate Frisbee, volleyball and squash) volunteered for the study. Participants were screened prior to performing the experiment using a visual assessment of acuity and stereoacuity, the University of Waterloo health history questionnaire, and the Waterloo handedness questionnaire (Locklin, Bunn, Roy & Danckert, 2010; Tapper et al., 2017). Acuity was measured using a Bailey-Lovie chart and stereoacuity was measured using the Randot Stereo book (Stereo Optical Company, Inc.). The

University of Waterloo health history questionnaire asked questions regarding medical history of concussion/traumatic brain injury (TBI), neurological disorders (e.g., chronic migraines, schizophrenia), affective mood disorders (e.g., depression, bipolar), cardiovascular disease (CVD), current use of medication affecting the central nervous system, and involvement in sport. Furthermore, a 22-question symptom checklist representing the participant's current feelings in emotional, cognitive and somatic health was completed using a six-point Likert scale ranging from zero (none) to six (severe). Finally, the Waterloo handedness questionnaire asked 34 questions concerning how often the participant uses their left or right hand to perform different tasks (e.g., writing, lifting objects, and brushing teeth).

All participants had normal or corrected-to-normal binocular (i.e., glasses or contact lenses) visual acuity < 0.10 logMAR, stereoacuity <50 seconds of arc, were never medically diagnosed with a concussion/TBI, neurological disorder, CVD, or were taking any medication affecting the central nervous system (e.g., anesthetics, muscle relaxants, narcotics, nonnarcotic analgesics). Seventeen participants were categorized as right-handed and three were left-handed. Two participants failed to meet the ERP inclusion criteria outlined in the data analysis section resulting in 18 participants included in the study (see Table 2.1). The study's protocol was approved by the University of Waterloo Research Ethics Committee.

Table 2.1

Participant Demographics [mean (standard deviation)]

	Male (n=7)	**Female (n=11)**
Age	25.85 (4.74)	22.18 (2.44)
Education	18.14 (3.13)	15.54 (2.84)
Acuity (Log MAR)	-0.1 – 0.0	-0.2 – 0.0
Stereoacuity (sec of arc)	28.57 (14.64)	30.45 (13.13)
Sport Type	Soccer, Basketball, Ice Hockey, Squash, Ultimate Frisbee	Soccer, Field Hockey, Ice Hockey, Rugby, Ultimate Frisbee, Volleyball
Sport experience (years)	20.00 (5.00)	13.54 (3.44)
Total Symptom score (max = 132)	1.85 (3.76)	1.36 (1.50)

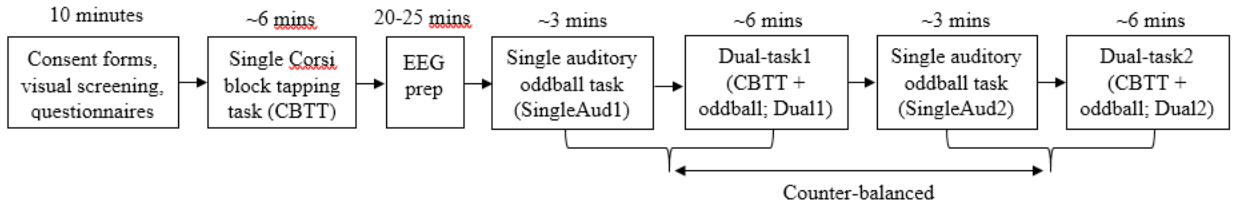
2.2.2 Materials and Procedures

Experimental Design

All participants completed the same blocked design experimental protocol sequence consisting of a single working memory task (i.e., eCorsi test), a single auditory oddball task (audsingle1), a dual-task (DT1), a second single auditory oddball task (audsingle2), and a second dual-task (DT2). The single auditory oddball tasks and dual-tasks were counterbalanced between participants (i.e., 10 participants performed audsingle1 and DT1 first, followed by an audsingle2 and DT2; while the other 10 participants performed audsingle2 and DT2 first, followed by an audsingle1 and DT1). The total testing protocol lasted approximately one-hour (see Figure 2.1).

Figure 2.1

Schematic diagram illustrating the collection protocol



Note. The single auditory condition (SingleAud1, SingleAud2) and dual-task conditions (Dual1, Dual2) were counterbalanced between participants.

eCorsi task

Behavioural data were collected using two computer systems. Presentation of the eCorsi (Corsi, 1973) block targets was controlled and recorded using a custom script written in VPixx 3.2.1 software (VPixx Technologies, Inc, QC, Canada). The eCorsi block test was displayed on a 22 x 14 inch Viewsonic LED monitor (resolution 1024x768-refresh rate 60 Hz) located in a soundproof booth using an Apple Macintosh laptop (OS X Mavericks, version 10.9). Subjects sat comfortably 60 cm from the centre of the monitor in an adjustable-height chair and were restricted from head movements using a chinrest. Participants remained in a chinrest and were instructed to fixate on a central fixation cross during eCorsi sequence presentation. A fixation cross-placed in the center of the screen was surrounded by eight black blocks (8mm x 8mm) displayed on a grey background (luminance = 92 cd/m^2). Each trial began when one block changed colour from black to white and remained illuminated for 750ms until the next block in the sequence changed colour. Only one block changed colour and remained illuminated at a time (see Figure 2.1). After the full sequence was displayed, participants were prompted by onscreen instructions to click on the central fixation using a mouse cursor with their preferred hand, and then recall the sequence of blocks in the order of presentation by clicking on each block using a mouse curser. Participants were allowed to move their eyes freely when recalling the sequence. The study involved seven levels for the eCorsi task, which corresponded to the number of blocks in the sequence that needed to be recalled. The easiest level involved a two-block sequence, and the difficulty was progressively increased up to eight blocks. Four trials were performed at each block sequence length. A different pattern was presented on each trial (i.e., no repeating patterns). Participants were presented with the same sequences, and completed all 28 trials (4 trials x 7 levels) regardless of the percentage of trials inaccurately recalled at each level.

Auditory Oddball Task

Auditory tone pips were created using VPixx 3.2.1 software presented binaurally at 60 decibels using two Altec Lansing computer speakers. One computer speaker was located on each side of the monitor. Participants remained in the chinrest located 60 cm from the centre of the monitor and were instructed to fixate on a central fixation cross during auditory tone presentation. Before testing, participants were presented with an iteration of high (1000Hz) and low (325Hz) tones and asked if they could discriminate between the two tones. All participants responded “Yes”, confirming they could correctly discriminate the two tones. Then, participants were instructed to respond by clicking a computer mouse with their preferred hand as quickly as possible when hearing a high tone (*probability* = 25%), and to withhold a response when hearing a low tone (*probability* = 75%). Every trial began with the participant clicking the central fixation followed by an iteration of high and low tones presented at a fixed interstimulus interval of 700ms. All participants performed seven levels with four trials per level. The first level started with four tones and progressively increased up to ten tones (level 7). Of the 196 tones presented throughout a single testing condition, 49 were high tones (target tone) and 147 were low tones (non-target tone).

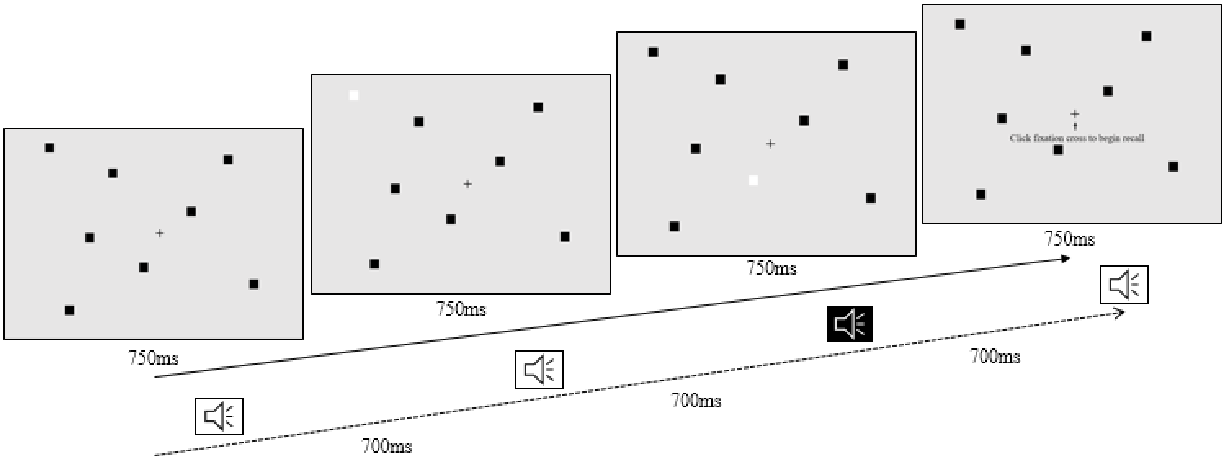
Dual-task

The third testing condition involved performing both eCorsi task and auditory oddball tasks simultaneously (see Figure 2.2). Similarly, participants clicked on the fixation cross to begin the trial while maintaining fixation on the central fixation cross. The auditory tones were presented every 700ms and the eCorsi blocks changed colour every 750ms. Participants had to respond to a high tone and withhold a response to a low tone while memorizing the eCorsi sequence. Importantly, the auditory task was only presented during the eCorsi encoding phase and not during the recall phase, which began after all the auditory tones were presented. Every participant was given the same instructions to "primarily focus on the Corsi task in the dual-task condition; therefore, if the task becomes too demanding you should neglect the auditory task to maintain performance on the Corsi task."

To increase the number of trials available for ERP analysis, a second block of single auditory oddball task and the dual-task was performed following the same protocol and instructions. The same number of trials (i.e., 28 trials total) were performed in both single and dual-task conditions resulting in equal number of eCorsi targets and auditory tones presented between task conditions (i.e., single, dual). In total 392 tones were presented in the single auditory oddball task, and 392 tones in the dual-task condition.

Figure 2.2

Schematic diagram displaying the dual-task timeline



Note. eCorsi trials began with presentation of all black blocks followed by the illumination of to-be-remembered blocks, shown in white. White blocks remained illuminated for 750ms. The auditory oddball task involved target tones (probability = 25%) embedded in a string of non-target tones (probability 75%). Auditory tones were presented every 700ms.

Electrophysiology

EEG data were recorded from 32 electrode sites (32 channel Quik-Cap, Neuroscan, Compumedics, NC, USA) according to the international 10-20 system for electrode placement with reference electrodes placed on the mastoids. The electrode impedance was <5kOhms; recordings were made with the filter set at DC-100 Hz and digitized at 500 Hz (Neuroscan 4.5, SynAmps2, Compumedics, NC, USA). EEG data were then saved for subsequent analyses.

2.2.3 Data Analysis

eCorsi task

The eCorsi task and the auditory oddball task behavioural data analyses were completed using VPixx 3.2.1 software and Microsoft Excel (MS Office 2016). For the eCorsi task, data exported from VPixx included the X and Y mouse response coordinates and response time (s). The X and Y coordinates were measured in millimeters from central fixation, which was defined as 0, 0. Negative values indicated responses made to the left and below central fixation whereas positive values indicated responses to the right and above fixation. A custom Excel script was developed to identify the participant's target order selection by comparing block location coordinates to the participant's mouse response coordinates. A target was considered correct if the participant's response coordinates fell within a 16 mm area of interest surrounding the target location (i.e., twice the size of the target), and was in the correct order of presentation. Response time (s) was measured as the time from central fixation click (i.e., beginning of recall).

In the literature, three scoring methods have been used to measure working memory capacity when using the eCorsi task: 1) the overall percentage of targets correctly recalled (i.e., eCorsi target accuracy), 2) the overall percentage of trials correctly recalled (i.e., eCorsi trial accuracy), and 3) spatial span defined as the longest sequence correctly reproduced on at least 50% of the trials of the same length. Research by Redick et al. (2012) reported partial storage scoring, defined as the sum of items recalled in the correct serial position throughout the whole task, to be the most reliable and sensitive measure for identifying individual differences in working memory capacity. Therefore, eCorsi target accuracy was used to measure working memory capacity in the current study because it is the same as partial storage scoring.

Auditory oddball task

For the auditory oddball task, exported VPixx data included timestamp of tone presented and the corresponding latency of responses. A custom Excel macro was developed to identify correct responses to high tones (i.e., auditory accuracy), errors of commission (i.e., false alarms – incorrectly responding to a non-target tone), and response time (RT) to correct tones. Auditory oddball accuracy (i.e., percentage of target tones correctly responded to), errors of commission (i.e., percentage of non-target tones incorrectly responded to), and auditory response time (i.e., response time to accurate target tones) were the main outcome measures used to assess performance as a function of mental workload. Responses to a target or non-target tone that were less than 110ms were excluded from the analysis because these are defined as anticipatory responses based on simple RT measures to an auditory stimulus (Kaur, Paul, & Sandhu, 2006).

Electrophysiology

EEG data analysis began by epoching, baseline correcting, and visually inspecting for artifacts (i.e., blinks, movement, and noise). Epoch duration was set to 600ms with a 100ms pre-stimulus baseline and 500ms post-stimulus interval. The latest potential of interest (i.e., P300 ERP) did not exceed the 500ms post-stimulus interval (M = 328.13ms, min = 250ms, max = 487ms). Epochs were eliminated from further analysis when the signal exceeded $\pm 50\ \mu$V or if the trial was incorrect (i.e., error of omission). A total of 98 target tones (high tones) and 294 standard tones (low tones) were collected per participant for each single and dual-task condition. Because the P50 ERP produces the smallest amplitude of interest, previous studies reporting on the P50 amplitude using the oddball task were used as a guide to determine the adequate number of trials per tone type, which was 31 (Oades et al., 1995) and 35 (Boutros et al., 1995) (target, non-target). Thus, to ensure an adequate signal-to-noise ratio, we excluded subjects if they had fewer than 40 trials per tone type (target, non-target) for each task condition (single, dual).

Event-related potentials were averaged separately for each tone type (i.e., target, non-target) then bandpass filtered using the following limits: high 0.5Hz and low 30Hz. Each participant's mean ERP amplitude and latency were computed using a baseline-to-peak method. The main auditory ERPs included P50 (40-80ms), N100 (80-170ms), and P300 (250-500ms).

Consistent with previous literature, ERPs were analyzed at electrodes where they were maximal in amplitude including P50-Cz, N100-Fz and P300-Pz (Duncan, Kosmidis, & Mirsky, 2003, 2005; Jones et al., 2016; Singhal et al., 2002; Solis-Marcos & Kircher, 2019). The influence of mental workload on sensory and cognitive ERPs was explored using the absolute amplitude for each tone (target, non-target) and for sensory gating (target subtracted by non-target).

2.2.4 Statistical Analysis

Statistical analyses were performed using SAS Studio software (version 9.04). Descriptive statistics are reported as means and standard deviations. Alpha level was set at 0.05 for post-hoc tests. The Eta squared (η^2) was used to measure effect size, which was calculated using $SS_{BETWEEN}$ divided by SS_{TOTAL} (Levine & Hullett, 2002). The statistical assumption of normality was tested for each behavioural and electrophysiological measure using the Shaprio-Wilk test and visually inspected using Q-Q plots.

eCorsi task

First, a paired t-test was performed on the two dual-task conditions to assess the difference in performance between blocks for the purpose of collapsing data into a single dual-task score. This analysis confirmed no significant differences between task conditions (dual1, dual2) t (17) = 0.44, p = 0.664; thus, dual-task scores obtained from the two blocks for each participant were averaged together.

The statistical tests of normality (Shapiro-Wilk test) did not reach significance; thus, parametric statistics were used to test the hypotheses.

Next, to ensure participants followed instructions by prioritizing the eCorsi task in the dual-task condition and to assess mental workload in each set size (i.e., number of blocks to remember), a two-way ANOVA was performed on dependent variable eCorsi recall accuracy. Two within-subject independent variables were task condition (Single, Dual) and set size (2 to 8 blocks). No differences between task conditions were expected for eCorsi accuracy because participants were instructed to prioritize the eCorsi in the dual-task (Tapper et al., 2016). Tukey-Kramer post hoc test was used to examine any significant differences between means and provided the rationale for splitting the auditory and ERP analysis into four mental workload conditions: single, dual easy, dual medium and dual hard.

Auditory oddball task

To test auditory oddball accuracy, two separate paired t-tests were performed on task conditions (single1 vs. single2 and dual1 vs. dual2) to assess the difference in performance between blocks for the purpose of collapsing data into one single-task and one dual-task score. This analysis revealed no significant difference between the two single-task conditions t (17) = 1.47, p = 0.159 or the dual-task conditions t (17) = 0.70, p = 0.492 conditions; thus, scores were averaged together by task condition.

The Shapiro-Wilk test on auditory accuracy was statistically significant ($p < 0.05$) and Q-Q plots showed the data were negatively skewed. Futher inspection showed a negative skew in the single-task, dual easy and dual medium conditions but had a normal distribution in the dual hard condition. Thus, auditory accuracy was converted to ranks (Conover & Iman, 1981; Conover, 2012; Zhuang et al., 2018) and tested using a one-way ANOVA using a within-subject factor mental workload (single-task, dual easy, dual medium, dual hard). Tukey-Kramer post hoc test was used to examine any significant differences between the means. All other behavioural and electrophysiological measures were normally distributed; thus, parametric statistics were used.

Next, a one-way ANOVA using within-subject mental workload (single-task, dual easy, dual medium, dual hard) was performed on dependent variables auditory errors of commission, and response time (correct tones). Multiple pairwise comparisons using a Tukey-Kramer adjustment were performed for any significant interaction or main effects.

Electrophysiology

To characterize sensory and cognitive processes as a function of mental workload, workload was categorized into four levels based on the behavioral analysis (i.e., single, dual easy, dual medium, and dual hard). Because auditory accuracy showed no difference across loads in the single-task condition, it was categorized as a single workload. Previous research has shown a stable and consistent P300 ERP amplitude using 20 trials recorded during an oddball task (Cohen and Polich, 1997), and this estimate of trial number is consistent with 14 trials that were analysed in a Go/No-Go task (Rietdijk, Franken and Thurik, 2014). In the current study all 18 participants had a minimum of 20 artifact free target and non-target epochs for each mental workload (single, dual easy, dual medium, dual hard) for the N100 and P300 ERPs. Because the signal-to-noise ratio was too low for the P50 ERP, workload was characterized by task condition (single, dual) where participants had a minimum of 40 artifact free target and non-target epochs.

To examine the early, “preattentive” sensory processing stage as a function of workload, a two-way ANOVA was performed on the amplitude of the P50 auditory ERP using two within-subject factors: task condition (single, dual) and tone type (target, non-target). Sensory gating (P50g) was analysed using an ANOVA with one within-subject factor, task condition.

To characterize the later, attentive sensory processing stage as a function of mental workload, a two-way ANOVA was performed on the N100 amplitude using two within-subject factors: workload (single, dual easy, dual medium, dual hard) and tone type (target, non-target).

In addition, sensory gating difference (N100g) was submitted to an ANOVA with one within-subject factor, workload (single, dual easy, dual medium, dual hard).

To examine cognitive processing as a function of workload, a one-way ANOVA was performed on the P300 target tone amplitude using one within-subject factor, workload (single, dual easy, dual medium, dual hard).

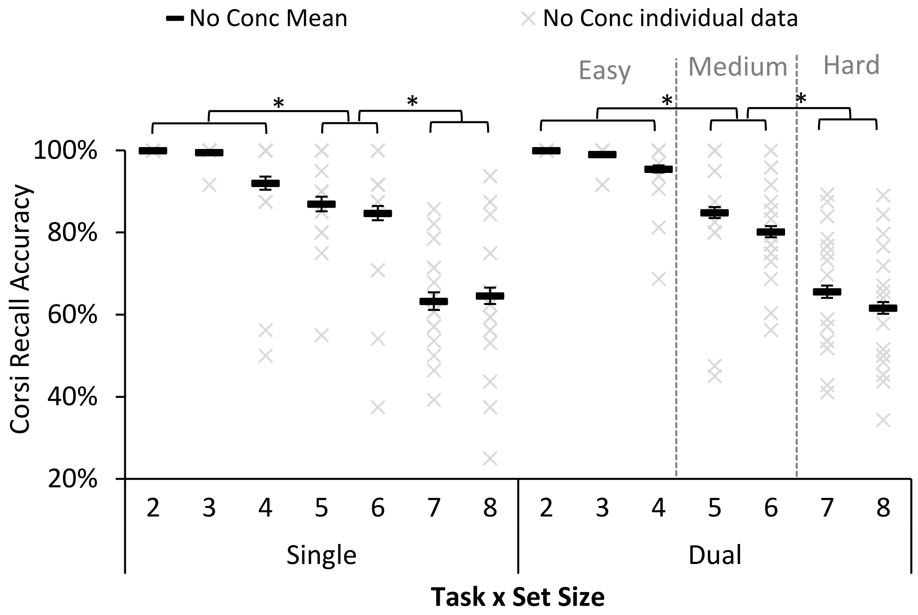
2.3 RESULTS

eCorsi task

The two-way ANOVA on eCorsi recall accuracy showed a main effect of set size F (6, 102) = 71.45 $P < .001$, $\eta^2 = 0.580$ (see Figure 2.3). Tukey-Kramer post hoc showed set sizes of two to four having significantly higher accuracy than sets of five to eight, and sets of five and six had higher accuracy compared to sets of seven and eight. This outcome provided the rationale for splitting the task into easy, medium and hard loads for the auditory and ERP data analysis. The effect of task or the interaction effect did not reach significance, which confirmed that participants prioritized the eCorsi task in the dual-task.

Figure 2.3

Corsi accuracy (represented as the % of targets correctly recalled)



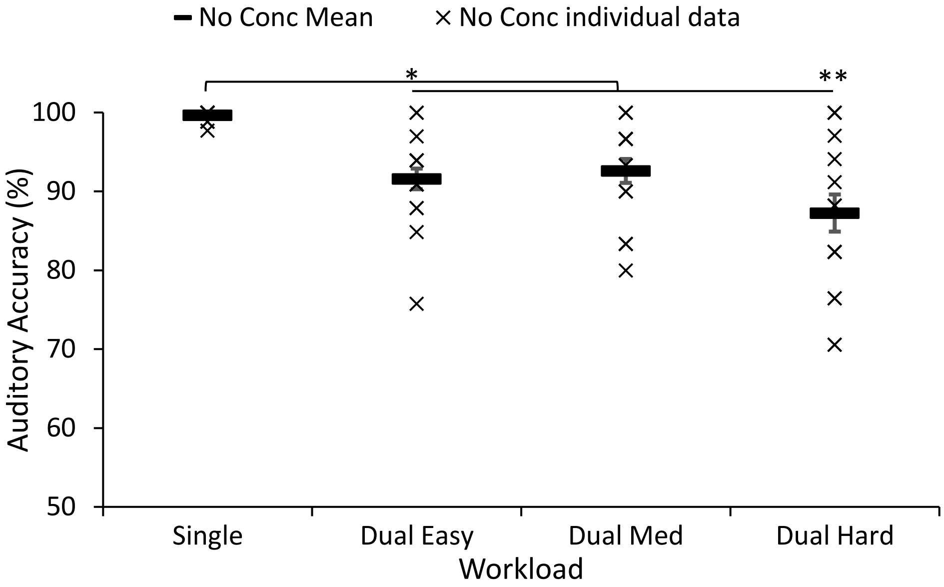
Note. The x-axis is separated by task condition (single, dual) and set size (2 to 8 blocks; easy, medium, hard). The graph shows the means (black bars) and individual data (light gray x). Recall accuracy decreased as set size increased from easy to medium (*) and medium to hard (*) but did not differ between task conditions.

Auditory oddball task

The one-way ANOVA computed on the ranks for auditory accuracy showed a significant main effect for mental workload F (3, 51) = 18.43 $P < 0.001$, $\eta^2 = 0.387$. Tukey-Kramer post hoc showed the single-task accuracy was significantly higher compared to all other conditions and, the dual hard condition had the lowest accuracy compared to all other conditions (see Figure 2.4). There were no significant differences between the other workloads. This confirmed that performing two tasks simultaneously reduces secondary task performance.

Figure 2.4

Auditory oddball accuracy (represented as the % of target tones correctly responded to)

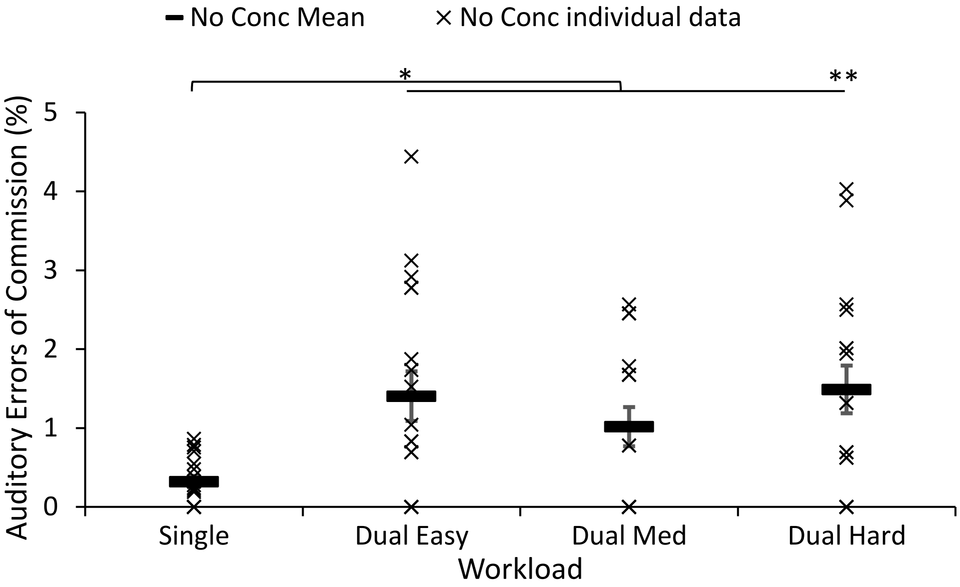


Note. The x-axis is separated by mental workload (single, dual easy, dual medium, and dual hard). The x symbols represent individual subject data and the black horizontal line represents the mean. Accuracy decreased as workload increased from single-task to dual-task (*), and were lowest in the dual hard workload (**).

The one-way ANOVA on auditory errors of commission (i.e., incorrectly responding to a non-target tone) showed a main effect for mental workload $F\ (3, 51) = 4.68\ P < 0.006$, $\eta^2 = 0.159$. Tukey-Kramer post hoc test showed a significantly higher percentage of errors of commission in the dual easy, dual medium and dual hard workloads compared to the single-task (see Figure 2.5).

Figure 2.5

Auditory errors of commission (represented as % of incorrect responses)

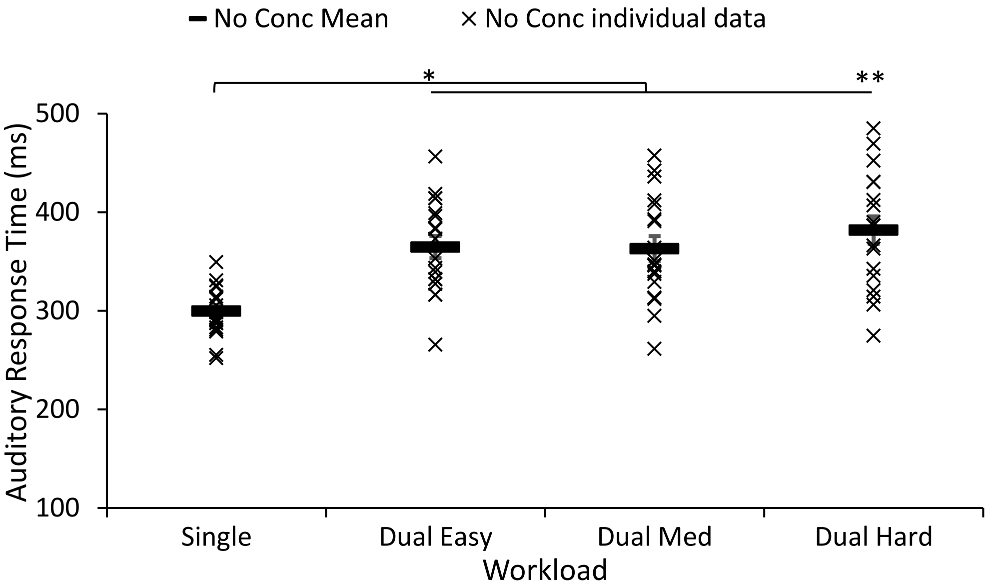


Note. The x-axis is separated by mental workload (single, dual easy, dual medium, and dual hard). The x symbols represent individual subject data and the black horizontal line represents the mean. Errors increased as workload increased from single-task to dual-task (*), and were highest in the dual hard workload (**).

The one-way ANOVA on auditory oddball response time revealed a significant main effect of mental workload $F\ (3, 51) = 33.51\ P < 0.001$, $\eta^2 = 0.307$. Tukey-Kramer post hoc showed longer response times in the dual easy, dual medium and dual hard workloads compared to the single-task, and longer response times in the dual hard workload compared to the dual easy and dual medium workloads (see Figure 2.6).

Figure 2.6

Auditory oddball response time (s)

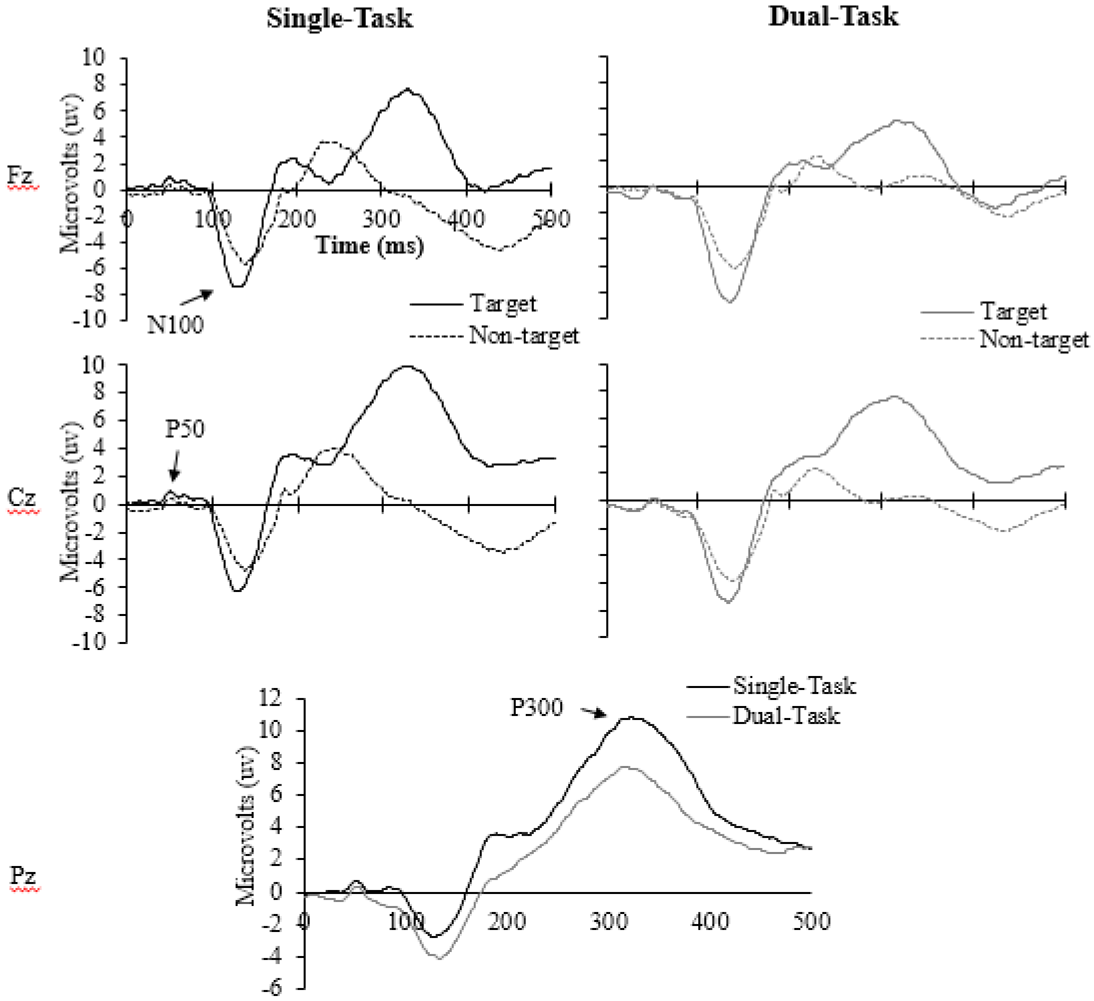


Note. The x-axis is separated by mental workload (single, dual easy, dual medium, and dual hard). The x symbols represent individual subject data and the black horizontal line represents the mean. Response time increased as workload increased from single-task to dual-task (*), and were longer in the dual hard workload (**).

The grand average ERP traces for each task condition (single, dual) are shown in Figure 2.7. ERP latencies were analysed first. A two-way ANOVA was performed on P50 and N100 ERP latency using independent factors workload (P50 = single, dual; N100 = single, dual easy, dual medium, dual hard) and tone type (target, non-target). A one-way ANOVA was performed on the P300 ERP target tone using workload (single, dual easy, dual medium, dual hard). Results showed a significant effect of workload on the P50 ERP latency F (1, 17) = 5.95, P = 0.026, η^2 =0.077 (Single: M = 60.16ms ± 11.9; Dual: M = 54.08ms ± 9.1). The N100 ERP latency showed a significant effect of tone type F (1, 17) = 9.01, P = 0.008, η^2 =0.089 (Target: M = 132.69ms ± 10.9; Non-target: M = 138.76ms ± 8.5). There was no effect of workload on N100 or P300 latencies.

Figure 2.7

Grand average ERP traces



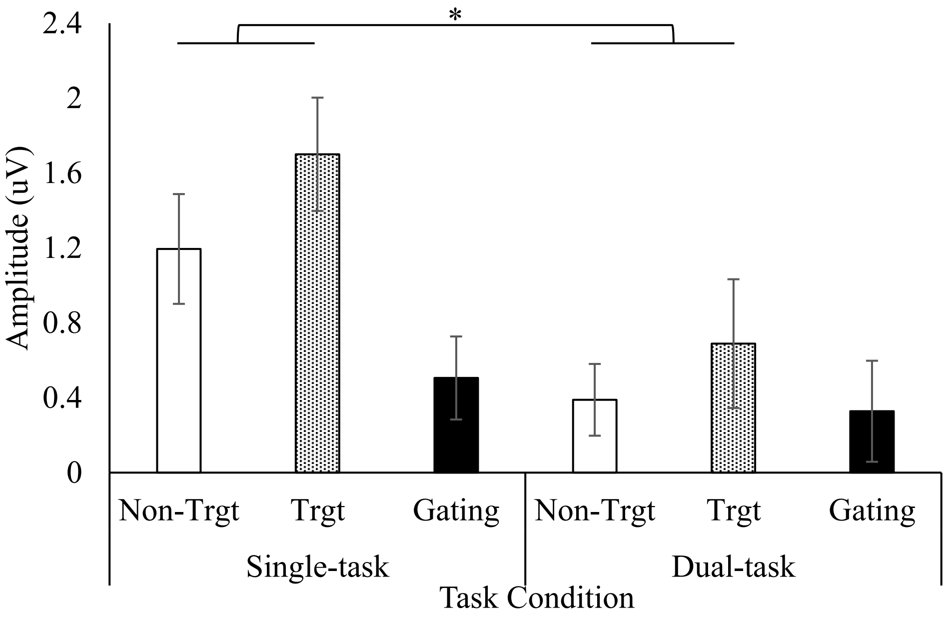
Note. Target (solid lines) and non-target tones (dashed lines) separated by task condition (single-task = black; dual-task = gray) and electrode (top = Fz, middle = Cz, bottom = Pz).

P50 preattentive sensory processing

The two-way ANOVA on P50 ERP amplitude using independent variables tone type and task condition (single, dual) showed a main effect of tone type $F\ (1, 17) = 5.48$, $P = 0.032$, $\eta^2 = 0.024$, and task condition $F\ (1, 17) = 13.72$, $P = 0.001$, $\eta^2 = 0.124$ (see Figure 2.8). A Tukey-Kramer post hoc revealed target tones elicited larger P50 amplitude than non-target tones, and single-task condition elicited larger P50 amplitude compared to the dual-task condition. The tone type by task condition interaction was not significant. The one-way ANOVA on P50 gating showed no effect of task condition $F\ (1, 17) = 0.36$, $P = 0.554$, $\eta^2 = 0.010$ (see Figure 2.8).

Figure 2.8

Average P50 amplitude and sensory gating



Note. Sensory gating was calculated by subtracting non-target amplitude from target and obtained from electrode Cz for each task condition (single, dual). Sensory gating did not differ between task conditions but the P50 amplitude magnitudes decreased in the dual-task compared to single-task.

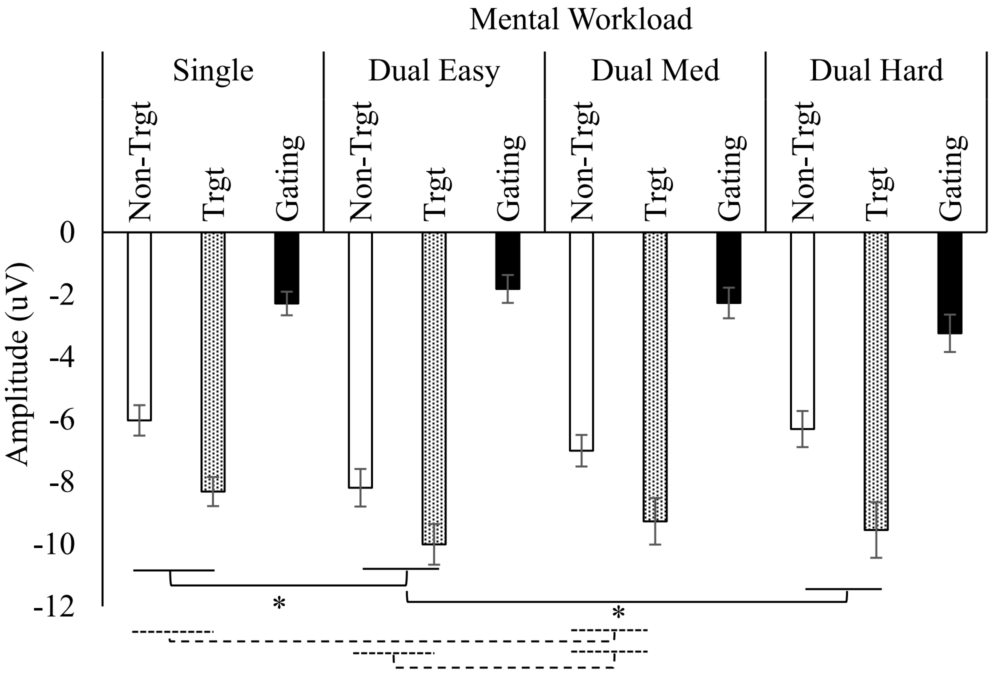
N100 attentive sensory processing

The two-way ANOVA on N100 ERP amplitude as a function of mental workload revealed a significant main effect of workload $F\ (3, 51) = 5.35$, $P = 0.002$, $\eta^2 = 0.054$ and tone type $F\ (1, 17) = 71.28$, $P < .001$, $\eta^2 = 0.165$. A Tukey-Kramer post hoc revealed smaller ERP amplitudes in the single workload condition compared to the dual easy workload, and a trend towards significance when single workload was compared to the dual-task medium condition ($p = 0.052$). There was no significant difference between single-task and dual-task hard condition.

In addition, N100 ERP amplitudes were significantly higher in the dual easy workload condition compared to the dual hard workload ($p < 0.05$). The difference between dual-task easy and dual-task medium was trending towards significance ($p = 0.052$). A Tukey-Kramer post hoc showed target tones elicited a larger N100 amplitude (i.e., greater negativity) than non-target tones across all mental workloads. There was no interaction effect as a function of workload and target type. The one-way ANOVA on N100 gating showed no effect of workload $F(3,51) = 1.73$, $P = 0.172$, $\eta^2 = 0.063$ (see Figure 2.9).

Figure 2.9

Average N100 amplitude and sensory gating



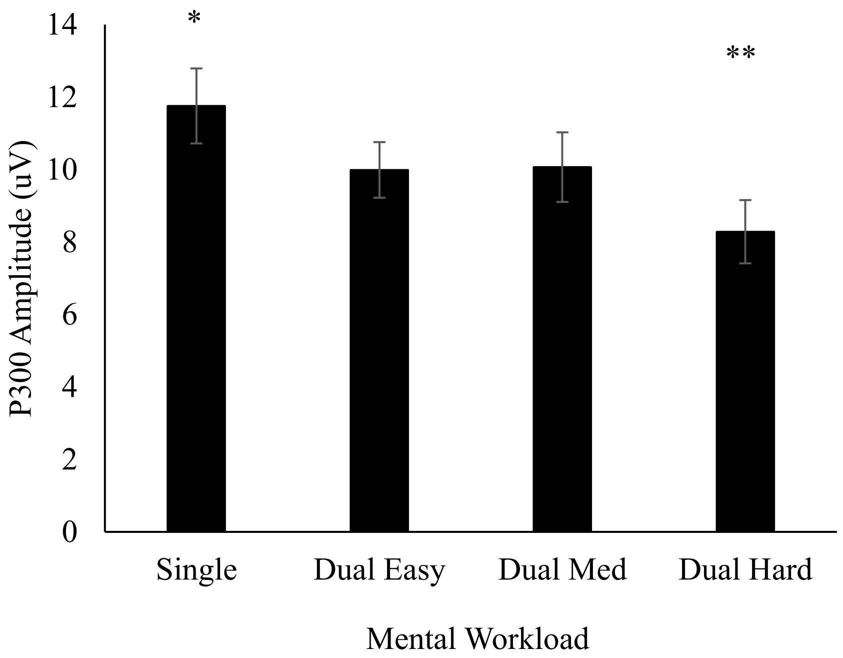
Note. Sensory gating difference (target – non-target) was obtained from electrode Fz for each mental workload. Solid lines represent significant effects (p < 0.05). Dashed lines represent trending significant (p = 0.052).

P300 cognitive process

The one-way ANOVA on P300 amplitude as a function of workload revealed a significant main effect of workload *F* (3, 51) = 8.95, *P* < .001, η^2 =0.089. A Tukey-Kramer post hoc showed the single workload having a significantly larger amplitude whereas the dual hard workload had the smallest amplitude. There was no significant difference between dual easy and dual medium workloads (see Figure 2.10).

Figure 2.10

Average P300 target tone amplitude



Note. P300 was obtained from electrode Pz. P300 amplitude was largest in the single-task and smallest in the dual hard workload.

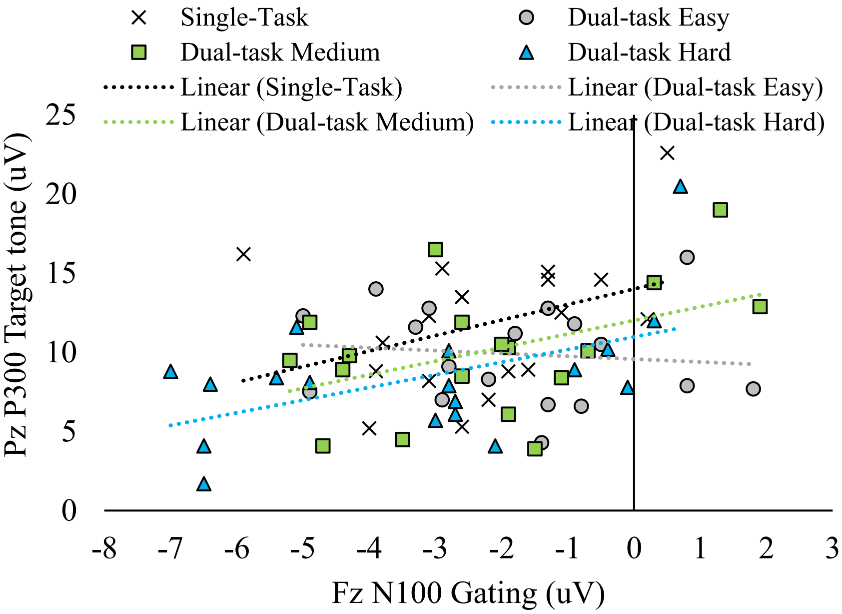
Association between sensory and cognitive ERPs

Sensory gating has been often thought of as a process that helps to reduce the amount of redundant information reaching higher order areas for cognitive processing. Therefore, we sought to assess the influence of sensory gating on the cognitive stage of information processing.

To test this we explored whether sensory gating, reflected by P50g and N100g ERPs (target tone minus non-target tone), was related to the availability or allocation of attentional resources at the cognitive stage of information processing, reflected by the P300 ERP amplitude. A Pearson product correlation analysis was performed using N100 sensory gating amplitude and P300 target amplitude separately for each workload (single, dual easy, dual medium, dual hard), and P50 sensory gating and P300 target amplitude for each task condition (single, dual). Results showed a significant correlation between N100 gating and P300 target amplitude in the dual-task hard workload r(17) = .506 (95% CI = 0.052, 0.786), p = 0.032 (see Figure 2.11). A larger N100 ERP sensory gating amplitude (i.e., greater negativity) was associated with a lower amplitude of the P300 potential, which might indicate that more efficient sensory gating reduces the amount of attentional resources allocated to the task at the later cognitive stages of information processing. This association was trending towards significance in the dual medium workload r(17) = 0.439 (95% CI = -0.035, 0.751), p = 0.069, but did not reach significance in the single-task r(17) = 0.358 (95% CI = -0.13, 0.706), p = 0.143 or dual easy workload r(17) = -0.109 (95% CI = -0.547, 0.377), p = 0.664. There were no significant associations between P50g and P300 target tone amplitude.

Figure 2.11

Association between N100 sensory gating and P300 target tone amplitude



Note. A Pearson product moment correlation was performed at each workload (single, dual easy, dual med, dual hard). The dual hard workload showed a significant positive correlation between N100 gating and P300 target amplitude.

2.4 DISCUSSION

The current study was designed to assess the effects of mental workload on sensory and cognitive auditory ERPs. Mental workload was manipulated by instructing participants to perform an auditory oddball task alone and simultaneously with an eCorsi task that progressively increased in set size. The main findings of this study are: 1) sensory gating effects were comparable across the workload conditions (P50: single, dual; N100: single, dual easy, dual medium, dual hard) as reflected by larger target compared to non-target P50 and N100 ERP amplitudes; 2) P50 ERP amplitude was reduced to both target and non-target tones in the dual-task condition compared to the single-task; 3) N100 ERP amplitude was higher for both tone types in the dual easy compared to the single-task and dual-task hard conditions; and 4) N100 ERP amplitude for both types of tones was comparable between the single, dual medium and dual hard workload conditions. These findings suggest that the P50 and N100 ERPs reflect early sensory gating mechanisms that are unaffected by mental workload (single versus dual/easy vs. medium vs. hard); however, the magnitude of these responses can be modulated by the imposed workload. In addition, cognitive stages of processing are impacted by workload, as reflected by a reduced P300 ERP amplitude. This is consistent with the hypothesis that the amount of attentional resources is reduced or that those attentional resources are allocated towards the primary eCorsi task when it increases in workload (i.e., set size). Interestingly, participants who gated information more efficiently (i.e., target ERP amplitude > non-target ERP amplitude) at a later sensory stage (N100 ERP), allocated fewer attentional resources towards target tones at the cognitive stage (P300). This novel finding may suggest that some participants direct their attention earlier to filter select relevant sensory information more efficiently whereas others rely more on later cognitive processing stages.

Our findings advance the understanding of how mental workload affects "preattentive" (P50) and attentive (N100) stages of sensory processing. Results showed target tone amplitudes were larger than non-target amplitudes (i.e., sensory gating) at both P50 and N100 ERPs regardless of workload (single versus dual/ dual easy, dual medium, dual hard). This finding is consistent with the initial view that the P50 and N100 ERPs reflect automatic "hard-wired" sensory gating processes that are insensitive to the load imposed by a task (Freedman et al., 1987). Previous research reported no effect of mental workload on P50 gating when participants simultaneously performed different cognitive tasks while passively listening to the paired click paradigm (Kho et al., 2003; Paleske, 2019; White & Yee, 1997; Yee & White, 2001). In contrast, Yee & White (2001) reported poorer P50 gating caused by a reduction in the ERP amplitude to the first auditory click when participants performed a mental arithmetic task aloud. However, this reduction may have been caused by the movement of facial muscles during speech or the competing auditory stimulation from hearing their own voice, both were shown to reduce P50 gating in the same study. Our findings are also in line with previous research on N100 ERP gating which has shown no effect of mental workload on N100 sensory gating (Kho et al., 2003; Harmony et al., 2000; Ullsperger et al., 2001). In particular, the amplitude to relevant stimuli (i.e., first click in paired-click paradigm and target stimulus in oddball task) were larger than irrelevant stimuli (second click and non-target stimulus). Thus, sensory gating at early (P50) and late (N100) stages of information processing appears to be unaffected by increases in mental workload in young team-sport athletes.

The size of the P50 ERP amplitude to target and non-target tones decreased when both tasks were performed simultaneously compared to performing the auditory oddball task alone. This finding is consistent with the view that early, sensory stages of information processing can be modulated by the direction of attention or other cognitive processes (Guterman, Josiassen, & Bashore, 1992; Kho et al., 2003; Yee et al., 2010) and would lead us to believe that the P50 ERP does not reflect a strictly "preattentive" sensory mechanism. Rather, the P50 ERP may reflect an early, attention regulation process where attention is triggered by an incoming target stimulus (i.e., exogenously) or attention acts to select relevant information (i.e., endogenously). The consistent P50 gating between task conditions but smaller tone amplitudes in the dual-task could represent an interaction between the "hard-wired" sensory gating process and attention regulation effect. For instance, more attentional resources were available during the single-task condition resulting in a larger P50 amplitude whereas fewer resources were available in the dual-task condition resulting in a reduced P50 amplitude; however, the hard-wired gating effect was maintained. These findings may suggest that the P50 ERP reflects an attentional gain control mechanism that can up-regulate processing of sensory information when resources are available and down-regulate when resources are allocated towards another task. This might become important when detecting relevant from irrelevant information where the ability to correctly discriminate targets from non-targets at an early stage improves when gain increases but begins to fail when gain decreases. Further research using more trials with increasing mental workloads may be able to more clearly disentangle these results as we did not have a sufficient number of ERPs to reliably measure the P50 response between the four workloads (single, dual easy, dual medium, dual hard); thus, they had to be collapsed into a dichotomous variable (single versus dual).

The amplitude of the N100 ERP for targets and non-targets increased when workload increased from single-task to dual easy, then decreased from dual easy to dual hard. These findings are different than most studies which reported smaller N100 amplitude magnitudes under dual-task conditions compared to single-task (Kasper et al., 2014; Miller et al., 2011; Singhal et al., 2002; Solís-Marcos & Kircher, 2019; Ullsperger et al., 2001). However, some studies have reported no difference between single-task and dual-task easy workloads (Miller et al., 2011) or between dual-task conditions that increase in mental workload (Harmony et al., 2000). In addition, one study reported a larger N100 amplitude (Ruiter, Kessels, Jansma, & Brug, 2006) in dual-task conditions that were hypothesized to impose a greater workload. Our results might help to explain the mixed findings presented in the literature, which could be dependent on the interaction between the degree of mental workload and the allocation of attentional resources. Specifically, tasks with low workloads that require little attention (i.e., single-task) are associated with a smaller N100 ERP amplitude. Then, as workload progressively increases (dual-task easy) more attention is needed, reflected in an increased N100 amplitude. Lastly, as workload exceeds attentional capacity, N100 amplitude decreases. The behavioural data would support the idea that capacity limits are approached because performance decreased drastically. Another not mutually exclusive explanation is that the effect of attentional regulation/ selection occurs later in the sensory processing when mental workload increases (i.e., dual-task) compared to performing the auditory task alone. This would explain why the P50 ERP amplitude was larger and N100 amplitude smaller in the single-task whereas the opposite was found in the dual-task condition (i.e., smaller P50, larger N100). Previous workload research has not examined the P50 response; thus, a direct comparison with other studies is not possible. Alternatively, it is possible that the dual-task condition caused a transient increase in arousal resulting in a larger N100 amplitude in the dual-task easy condition. Previous research has shown that the N100 amplitude can be facilitated by arousal (Naatanen & Näätänen, 1992; Nash & Williams, 1982); thus, participants may have become more aroused in the dual-task easy condition until they became familiar with the task because it was always performed in the same order (i.e., single, dual easy, dual medium, dual hard). Lastly, the effects could be due to a combination of the aforementioned possibilities.

Research into the neural generators of P50 and N100 ERPs shows overlapping neural networks mainly localized bilaterally in the temporal lobes; however, neuronal activity in the prefrontal areas is thought to play an important role in mediating these neural responses (Boutros et al., 2013; Korzyukov et al., 2007). These studies suggest that the P50 and N100 ERP amplitudes reflect a multistage sensory gating process that can be modulated by attention to either facilitate (“gate-in”) or inhibit (“gate-out”) sensory information. The exact neural generators reflected by each ERP are still under investigation; however, accumulating evidence from humans and primates using a combination of neuroimaging, intracranial electrodes, magnetoencephalography, and electroencephalography approaches used with the paired-click paradigm suggests that the prefrontal cortex and hippocampus could contribute to the early, sensory processing stage reflected by the P50 ERP, whereas the thalamus could contribute more to the later, sensory processing stage reflected by the N100 ERP (Arciniegas et al., 2001; Bowyer, Boutros, Korzyukov, & Tepley, 2007; Boutros et al., 1995, 2011, 2013; Guterman et al., 1992, Vlcek, Bob, & Raboch, 2014).

The role of each neural area in auditory processing and attentional selection is also still unclear; however, it has been proposed that the prefrontal cortex may directly excite excitatory neurons storing the neural memory trace for the target tone in the hippocampus and, at the same time, activate pyramidal inhibitory comparator neurons storing the non-target tone trace (Boutros et al., 2013; Vinogradova, 2001; Vlcek et al., 2014). This would produce a facilitated target tone response and a reduced non-target tone response reflecting the automatic "hard-wired" P50 gating phenomenon. However, if this system is not recruited properly, the prefrontal cortex can activate these neural memory traces through a cortical-thalamic-hippocampal pathway as reflected in the later, N100 gating response. This may be because the higher-order nuclei of the thalamus can be a conduit to gating (inhibition) at earlier modality-specific cortical areas resulting in greater contribution at the later, sensory processing stage. This would explain why individuals with a traumatic brain injury (Arciniegas et al., 2000), schizophrenia (Patterson et al., 2008; Yee et al., 2010; Sigurdsson & Duvarci, 2016) and Alzheimer's disease (Cancelli et al., 2006; Thomas et al., 2010) show little, if any P50 and N100 sensory gating because the neuronal populations within prefrontal and/or hippocampal areas are damaged or the neural pathways connecting these areas are affected. Our findings suggest that both neural pathways have a hard-wired gating response that can be upregulated by the direction of attention. For instance, our participants may have upregulated sensory information when attentional resources were available (i.e., single-task) using the prefrontal-hippocampal network causing larger P50 amplitude magnitudes (target and non-targets); however, when attention was consumed (i.e., dual-task condition), there was a delay in sensory processing resulting in participants having to rely more on the use of the prefrontal-thalamic-hippocampal pathway, reflected in larger N100 amplitude magnitudes. This may not be represented in a latency effect, rather, the inverse relationship between P50 and N100 amplitudes (i.e., larger P50, smaller N100 in single-task; smaller P50, larger N100 in dual-task).

Most research on the effect of mental workload on ERPs has focused on the later, cognitive stages of information processing, in particular the P300 ERP. Studies show decreased target tone amplitude when performing a primary visual task with a secondary auditory task (Kasper et al., 2014; Parasuraman, 1985; Ruiter et al., 2006; Singhal et al., 2002; Solis-Marcos & Kircher, 2019; Ullsperger et al., 2001; Wester et al., 2008), and this reduction is proportional to the difficulty of the primary task (Isreal et al., 1980; Wester et al., 2008). Our results replicate these findings showing smaller P300 amplitudes when two tasks are performed simultaneously, which decreased as a function of primary task workload (i.e., increase in set size). One of the most common views that explains our findings is that the P300 ERP reflects the amount of attentional resources available or the allocation of attentional resources at the cognitive stage of information processing (Kasper et al., 2014; Parasuraman, 1985; Ruiter et al., 2006; Singhal et al., 2002; Solis-Marcos & Kircher, 2019; Ullsperger et al., 2001; Wester et al., 2008). Importantly, the P300 amplitude might also be dependent on a person's ability to efficiently filter sensory information during the later, sensory processing stage because a larger N100 gating difference was associated with a smaller P300 target amplitude. Similar findings were reported by Ruiter et al., (2006) who found smaller P300 amplitudes and larger N100 amplitudes in their high compared to low mental workload condition, and suggested that participants selected information better in the sensory stage which required less effort in the cognitive processing stage. If the N100 ERP represents a sensory gating process and the P300 ERP reflects the allocation of attention then this would indicate an interaction between sensory and cognitive processing such that fewer attentional resources are needed when sensory information is processed more efficiently. Further investigation into what each ERP represents and the relationship between sensory and cognitive stages of information processing is needed to help us understand the mechanisms affected by varying the task demands.

One theoretical framework that can help to interpret our electrophysiological results is Lavie's load theory (Lavie & Dalton, 2014). Load theory describes how and when distractor information is filtered out, which is dependent on the type of load (perceptual or cognitive). Perceptual load is defined as the amount of attentional resources available to process sensory information in a limited capacity system. It states that both relevant and irrelevant stimuli are processed under low loads but selection occurs at a late stage whereas distractor information is filtered out (or not processed) at an early selection stage under high loads. Cognitive "executive" control load is defined as the ability to appropriately allocate attentional resources in accordance with stimulus-processing priorities in an unlimited capacity system where high cognitive loads are thought to affect the late-selection processes. Most paradigms studying perceptual load focus on distractor processing while performing a primary visual search task or spatially encoding coloured blocks in a single display into working memory (Konstantinou, Beal, Kin, & Lavie, 2014; Konstantinou & Lavie, 2013) whereas cognitive load focuses on distractor processing while maintaining items in working memory (Konstantinou et al., 2014; see detailed review by Murphy et al., 2016). In contrast, our dual-task paradigm involves the discrimination of relevant from irrelevant auditory information while simultaneously sequentially encoding items into working memory. Our behavioural results are consistent with findings from perceptual load studies showing a reduction in processing capacity when load of the primary task increased (i.e., encoding more items in WM) resulting in decreased secondary auditory task performance (Konstantinou et al., 2014; Murphy et al., 2016). Further support for our task representing perceptual load is how N100 sensory gating (i.e., early-selection) and P300 amplitude (i.e., late-selection) changed as dual-task load increased. In particular, participants appeared to gate-out irrelevant stimuli (i.e., larger N100 gating difference despite not reaching statistical significance) at an early-selection stage when load increased from dual easy to dual hard whereas more attentional resources were available at a late-selection stage (i.e., larger P300 amplitude) under low compared to high loads. This might provide some indication that the attentional filter moved to an early-selection phase under high loads. However, the movement of the attentional filter appears to be dependent on the individual as some participants gated information more efficiently to reduce the load at a late cognitive stage (larger N100 gating, smaller P300 amplitude) when workload was high (i.e, dual hard) whereas others dedicated more resources to late processing stages rather than early selection (smaller N100 gating, larger P300 amplitude). Therefore, simultaneously encoding items into working memory while performing an oddball task appears to place a greater load on perceptual processes because the attentional filter moved from late to early selection as workload increased but this was dependent on an individual's capacity to process information.

The current experiment had a few limitations. First, the minimum number of ERPs per workload condition was set at 20 based on the internal consistency of the P300 potential (Cohen and Polich, 1997; Rietdijk et al., 2014). Although, this may provide a reliable P300 measure, it may not be enough trials for the N100 ERP analysis. Earlier research often failed to report the number of trials per condition; however, they collected similar or fewer target tone trials/conditions compared to our study. Duncan et al., (2009) suggested a minimum of 40 artifact free trials per condition is sufficient depending on the paradigm. Due to the complexity of the task, we chose to decrease the number of trials at each set size to avoid participants from becoming mentally exhausted. Given what we have learned from this study, future research can modify the current protocol by increasing the number of trials at set sizes of four, six, and eight because these levels of difficulty included the largest frequency of tones (6, 8, and 10 tones/ trial) and provided a good indicator of easy, medium and hard workloads. A second limitation is that trial administration was self-paced in contrast to the traditional uninterrupted time interval used when administering the oddball task. As a result, some participants could have taken longer breaks between trials; however, this may be a potential benefit because it allowed them adequate rest to remain engaged in the task. Some research has shown that longer breaks between auditory oddball conditions can temporarily improve reaction time but not accuracy (Lim & Kwok, 2016); however, we do not know how this affects within-task (i.e., between trial) performance. Since our dual-task condition involved a recall phase for the Corsi blocks, methodological modifications were made to allow self-paced recall.

2.5 CONCLUSION

The present study provides evidence of changes in both sensory and cognitive stages of information processing as a function of progressive increases in mental workload. Our findings suggest that the P50 and N100 ERPs reflect automatic sensory gating mechanisms that can be up-regulated or down-regulated based on the availability or allocation of attentional resources. In addition, when mental workload increased fewer attentional resources were available at the cognitive stages of information processing, reflected in smaller P300 amplitudes. Interestingly, the ability to efficiently filter sensory information during the attentive sensory processing stage (i.e., N100) may reduce the amount of attentional resources required at the cognitive processing stages. Alternatively, this finding might indicate that these stages reflect a different process such that the N100 reflects an attentional selection component and the P300 reflects information being updated into working memory. This novel finding is important because it might suggest that people engage in different strategies to process information when mental workload increases; thus, only reporting P300 amplitude as a measure of mental workload may be misleading. As a result, future studies should continue to examine the relationship between ERPs that reflect sensory and cognitive processes as a function of mental workload because these mechanisms are sub served by many overlapping brain areas that appear to work together to efficiently process information.

Section 3 – *The chronic neurocognitive effects of concussion on sensory and cognitive processes*

3.1 INTRODUCTION

Understanding the long-term consequences of sports related concussions has become a growing concern because of their potential to lead to neurodegenerative disorders such as mild cognitive impairment, Alzheimer's disease or chronic traumatic encephalopathy (Guskiewicz et al., 2005 & 2007). Recent reports from the National Football and Hockey Leagues (NFL, NHL) suggest that most concussions are transient injuries where most players recover within four to seven days post injury (Casson, Viano, Powell, & Pellman, 2010; Izraelski, 2014). This notion has been supported as an athlete's cognitive performance and symptomology often return to normal within 10 to 14 days post injury when tested using clinical neuropsychological batteries (Iverson, Brooks, Collins, & Lovell, 2006; Makdissi et al., 2010; Pellman, Lovell, Viano, & Casson, 2006). In contrast, there is a growing evidence revealing persistent cognitive impairments in individuals with a history of concussion who are no longer symptomatic when they are tested using more demanding dual-tasks that stress attentional resources (Bernstein, 2002; Howell, Buckley, Lynall, & Meehan, 2018; Howell, Osternig, & Chou, 2018; Segalowitz, Bernstein, & Lawson, 2001; Tapper, Gonzalez, Roy, & Neichwiej-Szwedo, 2017). In addition, these individuals show changes in how sensory (Duncan, Kosmidis, & Markis, 2003; Duncan et al., 2005; Gosselin, Theriault, Leclerc, Montplaisir, & Lassonde, 2006; Ruiter et al., 2019) and cognitive (Bernstein, 2002; Broglio et al., 2009; De Beaumont et al., 2006; Gosselin et al., 2006; Ozen et al., 2013; Rousseff et al., 2006; Segalowitz et al., 2001) information is processed suggesting persistent dysfunction to the underlying information processing network. As a result, research has begun to investigate how the central nervous system (CNS) processes information during more cognitively demanding tasks in an effort to identify the neural correlates associated with cognitive dysfunction following a concussion.

Many studies have suggested that event-related potentials (ERPs) can be used to investigate information processing deficits following a concussion (Bernstein, 2002; Broglio et al., 2009; De Beaumont et al., 2006; Gosselin et al., 2006; Ozen et al., 2013; Pratap-Chand, Sinniah, & Salem, 1988; Rousseff et al., 2006; Segalowitz et a., 2001). In particular, the P300 ERP component has been investigated extensively in participants who have suffered a concussion suggesting that these individuals either have fewer attentional resources or difficulty with properly allocating resources at the cognitive stages of information processing. For example, a seminal study by Pratap-Chand and colleagues (1988) revealed that P300 amplitude was reduced in individuals who had recently suffered a cerebral concussion (within four days) compared to controls when performing an auditory oddball task. However, this effect was short-lived, as longer repeat testing intervals (> 30 days) showed no between group differences, suggesting that information processing capacity was restored in those with a concussion. Importantly, this study led to an abundance of research examining cognitive ERPs, such as the P300 potential, using the auditory oddball task in individuals who sustained a concussion months to years prior but no longer experienced symptoms (Bernstein, 2002; Broglio et al., 2009; De Beaumont et al., 2006; Gosselin et al., 2006; Rousseff et al., 2006; Segalowitz et al., 2001). These studies revealed that P300 amplitude was significantly reduced in individuals with a history of concussion who were asymptomatic providing evidence that concussions cause long-term dysfunction at the cognitive stages of information processing. As a result, the P300 has become a useful ERP to evaluate information-processing deficits in individuals with a history of concussion.

On the other hand, relatively fewer studies have investigated sensory ERPs in individuals with a history of concussion. For example, the P50 and N100 are two sensory ERPs elicited by an auditory stimulus, which may reflect a multistage sensory gating process that protects higher order cognitive areas from being bombarded with sensory stimuli (Boutros, 1995; Boutros et al., 1999; Ermutlu et al., 2007; Knight et al., 1999). This gating process is carried out by facilitating incoming relevant information and/or inhibiting irrelevant stimuli (Braff & Geyer, 1990). Studies examining sensory ERPs during the auditory oddball task have yielded mixed results in individuals with a history of concussion (Bernstein, 2002; Duncan et al., 2003, 2005; Gosselin et al., 2006; Ruiter et al., 2019; Segalowitz et al., 2001). For instance, some studies reported smaller N100 amplitudes in individuals with a history of concussion compared to controls (Duncan et al., 2003, 2005; Gosselin et al., 2006; Ruiter et al., 2019); in contrast, other studies report no differences between groups (Bernstein, 2002; Segalowitz et al. 2001). The mixed findings could be the result of different analytic procedures as studies reporting no amplitude differences only analyzed target trials whereas those showing smaller amplitudes in concussed participants compared target to non-target trials. This is particularly important because sensory gating is often calculated using the difference between target and non-target amplitudes; thus, studies reporting smaller N100 amplitudes could reflect poorer target facilitation, non-target inhibition or a combination of the two. Thus, concussions might be associated with long-term problems that occur at the sensory stages of information processing.

There is a dearth of research on the P50 ERP in individuals with a history of concussion. One study by Arciniegas et al., (2000) showed changes to the P50 amplitude in individuals with a history of mild, moderate and severe traumatic brain injury (TBI) using the paired click paradigm. Specifically, they showed individuals with a history of TBI, regardless of severity, had significantly smaller amplitudes in response to the first auditory click, and significantly larger amplitudes to the second auditory click compared to controls. This finding indicated that those with a history of TBI had persisting problems gating in incoming relevant information (first click) and gating out irrelevant (second click) auditory information. However, one limitation was that participants were only classified according to post-traumatic amnesia; thus, some participants in the mild TBI group had similar Glasgow coma scale scores as those in the moderate to severe groups. A more recent study (Papesh et al., 2019) showed no P50 amplitude differences in military service members with and without a history of TBI sustained from a blast exposure using the paired click paradigm. The authors suggested that the cohort in their study had less severe injuries compared to prior research (Arciniegas et al., 2000), whose participants also complained of persisting cognitive impairments. These findings suggest that the severity of injury may play a significant role in persisting sensory processing dysfunction, and more specifically, deficits in sensory gating, which could in turn affect cognitive processing. No research to our knowledge has examined the P50 ERP using more demanding tasks in individuals with a history of concussion. It is important to understand how early and later sensory, as well as cognitive processes are affected by concussion in order to have a comprehensive understanding of long terms consequences of brain injury.

Therefore, the purpose of the current study was to investigate the sensory and cognitive ERPs in individuals with a history of concussion using a modified version of a dual-task paradigm shown to discriminate those with and without a history of concussion (Tapper et al., 2017). Since prior research with previously concussed individuals has shown subtle cognitive deficits using more cognitively demanding tasks, we manipulated task difficulty at two levels including set size (# of items to be remembered) and task condition (single, dual). This approach can help to identify which workload discriminates between those with and without a history of concussion. In addition, it allowed us to study the neural information processing mechanisms that might contribute to the behavioural deficits in those with a history of concussion. We hypothesized that P50 & N100 sensory gating and P300 amplitude will be reduced in participants with a history of concussion because concussions cause microstructural damage to the frontal-parietal networks involved in sensory and cognitive processing.

3.2 METHODS

3.2.1 Participants

Sixteen varsity and recreational athletes with a history of concussion participated in the study (6 females, 10 males). Four participants failed to meet ERP inclusion criteria (2 females, 2 males) resulting in 12 participants included in the study. In order to be included in the concussion group, the concussion must have been diagnosed by a medical professional (i.e., physician, physiotherapist). Eighteen participants without a history of concussion were matched from study one for between group comparisons (concussion, no-concussion).

Table 3.1

Participant Demographics [mean (standard deviation)]

	Male (n=8)	**Female (n=4)**
Age	23.87 (3.97)	23.00 (3.91)
Education	17.50 (3.29)	17.50 (4.12)
Acuity (Log MAR)	0.1 – 0.0	-0.1 – 0.0
Stereoacuity (sec of arc)	34.38 (13.48)	21.25 (2.5)
Sport Type	Soccer, Ice Hockey, Volleyball, Ultimate Frisbee, Basketball	Rugby, Basketball, Ice Hockey, Soccer
Sport experience	17.75 (5.09)	15.00 (8.12)
Total Symptom score (max = 132)	0.87 (1.24)	4.25 (0.95)
# of Concussions	1.63 (0.92)	1.75 (0.50)
# of participants reported being Knocked Unconscious	3	1
Time since most recent concussion (mos.)	83.63 (54.18)	41.50 (28.53)

3.2.2 Materials and procedures

The same study procedures and experimental design were followed as outlined in study 1 (section 2.2.2) including, basic visual assessment (acuity, stereoacuity), University of Waterloo health history questionnaire, and Waterloo handedness questionnaire.

3.2.3 Data Analysis

Behavioural

eCorsi task performance was measured as the percentage of targets recalled and auditory oddball performance was measured as the percentage of target tones responded to, the percentage of errors of commission, and response time (s) to correctly responded target tones.

Electrophysiological

The same electrophysiological procedures were followed as outlined in section 2.2.2 and 2.2.3. Briefly, EEG was collected according to the international 10-20 system with primary interest at electrodes Fz, Cz, and Pz. ERPs were epoched at a 100ms pre-stimulus baseline to 500ms post-stimulus with artifacts exceeding ±50 μV removed. The P50 (40-80ms), N100 (80-170ms) and P300 (250-500ms) amplitudes for target and non-targets were evaluated. Participants were excluded if they had fewer than 20 artifact free target and non-target epochs for the N100 and P300 ERPs at each workload condition (single, dual easy/medium/hard) and fewer than 40 for the P50 ERP at each task condition (single, dual). Twelve of the 16 participants met this inclusion criteria.

3.2.4 Statistical Analysis

Statistical analyses were performed using SAS Studio software (version 9.04). Descriptive statistics are reported as means and standard deviations. Alpha level was set at 0.05 for post-hoc tests. The Eta squared (η^2) was used to measure effect size, which was calculated using $SS_{BETWEEN}$ divided by SS_{TOTAL} (Levine & Hullett, 2002). The statistical assumption of normality was tested using the Shapiro-Wilk test and visually inspecting Q-Q plots, and homogeneity of variance between groups were tested using Bartlett's test for each behavioural and electrophysiological measure.

eCorsi task

First, a paired t-test was performed on the dual-task conditions to assess the difference in performance between blocks for the purpose of collapsing data into a single dual-task score. This analysis confirmed no significant differences between task conditions (dual1, dual2) t (11) = 1.80, p = 0.099; thus, dual-task scores were averaged together.

The statistical tests of normality (Shapiro-Wilk test) and homogeneity (Bartlett's test) did not reach significance; thus, parametric statistics were used to test the hypotheses.

A three-way mixed ANOVA was conducted on the eCorsi recall accuracy with one between-subject factor: concussion history (no concussion, concussion), and two within-subject factors: task condition (single, dual), and set size (2 to 8 blocks). No differences between task conditions were expected for eCorsi accuracy because participants were instructed to prioritize the eCorsi in the dual-task (Tapper et al., 2016). Tukey-Kramer post hoc test was used to examine any significant differences between means and provided the rationale for splitting the auditory and ERP analysis into four mental workload conditions: single, dual easy, dual medium and dual hard.

Auditory oddball task

To test auditory oddball accuracy, two separate paired t-tests were performed on task conditions (single1 vs. single2, dual1 vs. dual2) to assess performance between blocks for the purpose of collapsing data into one single-task and one dual-task score. Results showed no significant difference between single-task conditions t (11) = 0.38, p = 0.708 or dual-task conditions t (11) = 0.17, p = 0.869; thus, scores were averaged together by task condition.

The Shapiro-Wilk test on all auditory measures (accuracy, errors of commission or response time) in the concussion group did not reach statistical significance and Q-Q plots showed the data were normally distributed. Homogeneity of variance (Bartlett's test) was violated for auditory accuracy X^2 (1, N = 30) = 4.57, $P = 0.032$, but not for errors of commission or response time. Thus, auditory accuracy was converted to ranks (Conover & Iman, 1981; Conover, 2012; Zhuang et al., 2018) and tested using a two-way mixed model ANOVA with between-subject factor concussion history, and within-subject factor mental workload (single-task, dual easy, dual medium, dual hard). Tukey-Kramer post hoc test was used to examine any significant differences between the means.

Next, two separate two-way mixed model ANOVAs were conducted on dependent variables errors of commission and response time to target tones. The between-subject factor was concussion history, and the within-subject factor was mental workload (single-task, dual easy, dual medium, dual hard). Tukey-Kramer post hoc test was used to examine any significant differences between the means. Since the oddball task was the secondary task, it was hypothesized that the concussion participants would have a greater decrease in accuracy, more errors of commission and longer response times in the dual-task workloads compared to the non-concussed group.

Event-related potentials

The Shapiro-Wilk test (normality) and Bartlett's test (homogeneity of variance) were not statistically significant ($p > 0.16$) indicating that all electrophysiological measures were normally distributed and groups had similar variances.

To test whether early, sensory processing is affected by a history of concussion (no concussion, concussion), task condition (single, dual), and tone type (target, non-target), a three-way mixed model ANOVA was performed on the amplitude of the P50 ERP. The P50 ERP was analyzed by task condition because we did not have a sufficient number of ERPs to reliably measure the P50 response between the four workloads (single, dual easy, dual medium, dual hard). It was hypothesized that a main effect of tone type would be present showing larger P50 target tone amplitudes compared to non-target tones in both groups; however, there was no hypothesis between groups because no research to our knowledge has examined the P50 ERP using the oddball task in individuals with a history of concussion. In addition, the P50 sensory gating difference (P50g = target – non-target) was analysed using an ANOVA with factors concussion history and task condition.

To test whether the later, sensory processing changes as a function of concussion history and mental workload, a three-way mixed model ANOVA was performed on the N100 ERP amplitude using two within-subject factors: workload (single, dual easy, dual medium, dual hard) and tone type (target, non-target), and one between-subject factor: concussion history (no concussion, concussion). In addition, the N100 sensory gating difference (N100g = target – non-target) was analysed using an ANOVA with factors concussion history and mental workload. It was hypothesized that individuals with a history of concussion would have poorer sensory gating (Duncan et al., 2003, 2005; Gosselin et al., 2006; Ruiter et al., 2019).

To test cognitive processing stages, a two-way mixed model ANOVA was performed on the P300 target tone amplitude using one between-subject factor: concussion history and one within-subject factor: mental workload. Consistent with previous literature (Bernstein, 2002; De Beaumont et al., 2009; Gosselin et al., 2006; Ozen et al., 2013; Segalowitz et al., 2001), it was hypothesized that the concussion individuals would have smaller P300 ERP amplitudes in all workload conditions compared to the non-concussed group.

3.3 RESULTS

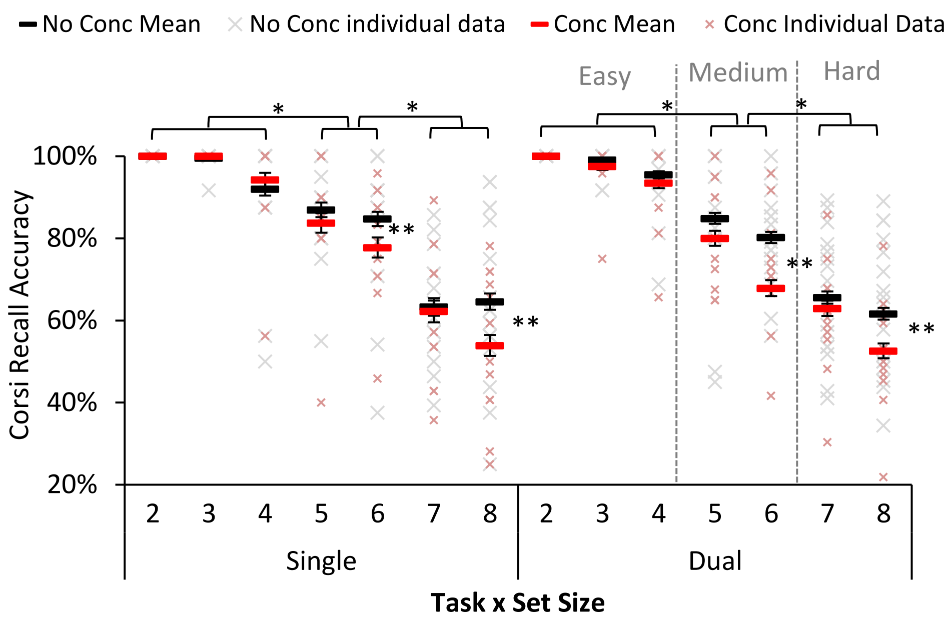
The between groups t-test on frequency of symptoms showed no significant differences t (28) = 0.08, $p = 0.468$. This was expected because all participants had returned to regular activity and reported being asymptomatic prior to testing.

eCorsi task

The three-way ANOVA on eCorsi recall accuracy showed a concussion history by set size interaction $F\,(1, 28) = 2.22$, $P = 0.044$, $\eta^2 = 0.010$. Tukey-Kramer post hoc showed both groups had higher recall accuracy for set sizes of 2-4 blocks (easy workload) compared to 5-6 blocks (medium workload) ($p < 0.001$) and 7-8 blocks (hard workloads) ($p < 0.001$), and the medium workload had a higher accuracy compared to the hard workload ($p < 0.001$) (Figure 3.1). Unexpectedly, individuals with a concussion had lower recall accuracy at set sizes of six and eight. There was a significant main effect of set size $F\,(6, 168) = 130.31$ $P < 0.001$, $\eta^2 = 0.590$, but no significant main effect of concussion history $F\,(1, 28) = 1.35$, $P = 0.256$, $\eta^2 = 0.008$, or task condition $F\,(1, 28) = 3.46$, $P = 0.074$, $\eta^2 = 0.001$. This finding supported our hypothesis that both groups prioritized the eCorsi task in the dual-task condition but did show differences between groups as a function of set size. There was no significant three-way interaction.

Figure 3.2

Corsi Accuracy (represented as % of blocks recalled)



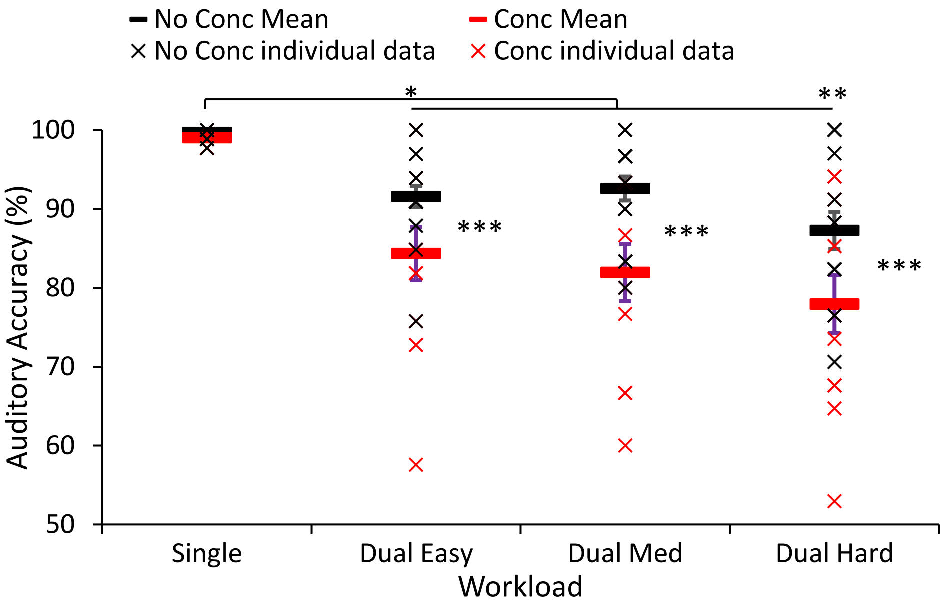
Note. The x-axis is separated by task condition (single, dual), set size (2 to 8 blocks; easy, medium, hard) and group (no concussion [No Conc], concussion [Conc]). The graph shows the means of each group (No Conc = black bars; Conc = red bars) and individual data (No Conc = light gray x; Conc = light red x). Recall accuracy decreased as set size increased from easy to medium (*) and medium to hard (*) but did not differ between task conditions. The concussion group recalled fewer blocks at a set size of six and eight (**).

Auditory oddball task

The two-way mixed ANOVA computed on the ranks of auditory accuracy showed a significant concussion history by mental workload interaction F (3, 84) = 3.13, $P = 0.030$, $\eta^2 = 0.030$. Tukey-Kramer post hoc test showed the concussion group had significantly lower accuracy in the dual easy ($p < 0.001$), dual medium ($p < 0.001$), and dual hard ($p < 0.010$) workloads compared to the no-concussion group but no significant between group differences were found in the single-task workload (p = 0.79) (Figure 3.2). This supported our hypothesis that individuals with a history of concussion would perform worse on the secondary auditory task in the dual-task workloads compared to the no-concussion control group. In addition, the concussion group had lower accuracy in the dual medium and dual hard workloads compared to their dual easy workload whereas the no concussion group had lower accuracy in the dual hard workload compared to their dual easy and dual medium workloads. Both main effects were present including, concussion history *F* (1, 28) = 9.33, *P* = 0.005, η^2 = 0.101, and mental workload *F* (3, 84) = 32.39, *P* < 0.001, η^2 = 0.314.

Figure 3.2

Auditory oddball accuracy (% of target tones correctly responded to)



Note. The x-axis is separated by workload condition (single, dual easy, dual medium, dual hard). The graph shows the means for the No Conc (black bars) and Conc (red bars) and individual data. Both groups had lower accuracy in the dual-task workloads compared to single task (*) and in the dual-task hard condition (**), but those in the concussion group had lower accuracy compared to the no concussion group in all dual-task workloads (***).

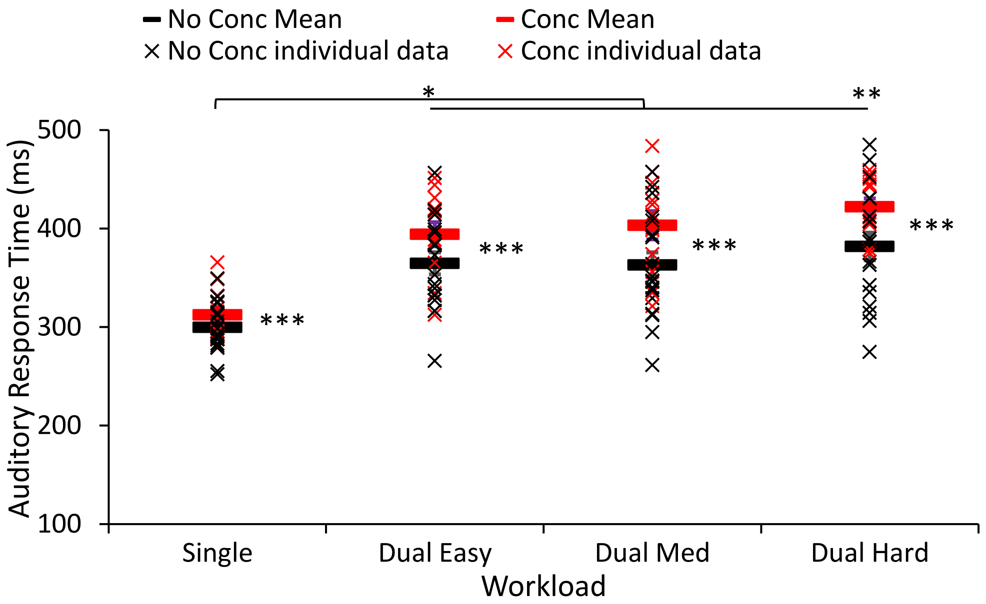
The two-way mixed ANOVA on auditory errors of commission revealed a significant main effect of concussion history *F* (1, 28) = 12.56, *P* = 0.001, η^2 = 0.087, and mental workload *F* (3, 84) = 13.50, *P* < 0.001, η^2 = 0.230. A comparison of the means showed the concussion group made a significantly higher percentage of errors compared to the no concussion group.

Tukey-Kramer post hoc showed the dual easy, dual medium and dual hard workloads having a higher percentage of errors compared to the single-task ($p < 0.001$) but no differences were present between dual-task workloads (No Concussion: single-task = 0.31% ± 0.30, dual easy = 1.40% ± 1.33, dual medium = 1.01% ± 1.05, dual hard = 1.48% ± 1.28; Concussion: single-task = 0.32% ± 0.31, dual easy = 2.69% ± 1.84, dual medium = 2.05% ± 1.71, dual hard = 2.67% ± 1.38). The concussion history by mental workload interaction did not reach statistical significance $F\ (3, 84) = 1.75$, $P = 0.162$, $\eta^2 = 0.027$.

The two-way mixed ANOVA on auditory response time revealed a significant main effect of concussion history $F\ (1, 28) = 4.58$, $P = 0.041$, $\eta^2 = 0.067$, and mental workload $F\ (3, 84) = 76.05$, $P < 0.001$, $\eta^2 = 0.380$. A comparison of the means showed the concussion group had significantly longer response times compared to the no concussion group. Tukey-Kramer post hoc showed longer response times in the dual easy, dual medium and dual hard workloads compared to the single-task, and longer response times in the dual hard workload compared to the dual easy and dual medium workloads (Figure 3.3). This finding supports our hypothesis that individuals with a history of concussion have longer response times when the workload increases; unexpectedly, response times were longer in the concussion group in the single-task condition compared to the no concussion group. The concussion history by mental workload interaction did not reach statistical significance $F\ (3, 84) = 1.81$, $P = 0.152$, $\eta^2 = 0.009$.

Figure 3.3

Auditory response time (milliseconds)



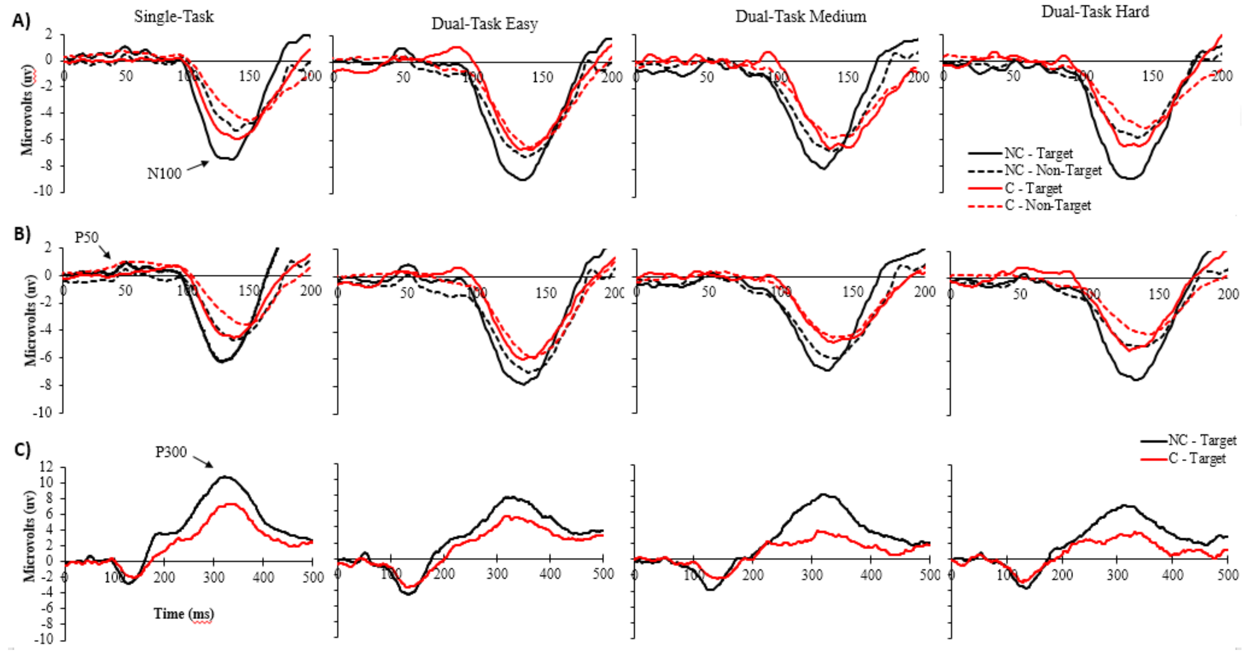
Note. Response times were longer in the dual-task workloads compared to single-task (*), in the dual hard compared to dual easy and dual medium workloads (**), and in those with a history of concussion compared to those with no concussion (***).

ERPs related to auditory oddball task

The grand average ERP traces for each mental workload condition are shown in Figure 3.4. ERP latencies were analysed first. A three-way ANOVA was performed on the P50 and N100 ERP latency using one between-subject factor concussion history (no concussion, concussion), and two within subject factors: workload (P50 = single, dual; N100 = single, dual easy, dual medium, dual hard) and tone type (target, non-target). A two-way ANOVA was performed on the P300 ERP latency to target tones using concussion history and workload (single, dual easy, dual medium, dual hard). Results for the P50 ERP latency showed a significant main effect of workload $F\ (1, 28) = 14.68$, $P < 0.001$, $\eta^2 = 0.098$ (Single: $M = 61.53$ms ± 11.9; Dual: $M = 54.16$ms ± 11.09) and tone type $F\ (1, 28) = 4.85$, $P = 0.036$, $\eta^2 = 0.024$ (Target: $M = 59.51$ms ± 12.7; Non-target: $M = 56.18$ms ± 11.5). The N100 ERP latency showed a significant main effect of concussion history *F* (1, 28) = 7.49, *P* = 0.011, η^2 =0.088 (No-concussion: *M* = 135.73ms ± 10.2; Concussion: *M* = 141.33ms ± 11.8), tone type *F* (1, 28) = 14.36, *P* < .001, η^2 =0.057 (Target: *M* = 132.69ms ± 10.9; Non-target: *M* = 138.76ms ± 8.5) and workload *F* (3, 84) = 3.55, *P* = 0.018, η^2 =0.027. Tukey-Kramer post hoc showed the single-task had longer latencies compared to the dual-task workloads (*p* < 0.001), which had no differences in latency (Single: *M* = 141.1ms ± 11.3; Dual-easy: *M* = 136.81ms ± 11.7; Dual-med: *M* = 136.95ms ± 11.9; Dual-hard: *M* = 137.01ms ± 9.4). The P300 ERP latency showed a significant main effect of workload *F* (3, 84) = 2.90, *P* = 0.039, η^2 =0.045. Tukey-Kramer post hoc showed longer latencies in the dual easy compared to dual medium and dual hard workloads (Single: *M* = 329.20ms ± 31.8; Dual-easy: *M* = 341.46ms ± 46.0; Dual-med: *M* = 317.46ms ± 36.1; Dual-hard: *M* = 324.33ms ± 52.5). No other effects reached statistical significance for P50, N100 or P300 latency.

Figure 3.4

Grand average ERP traces



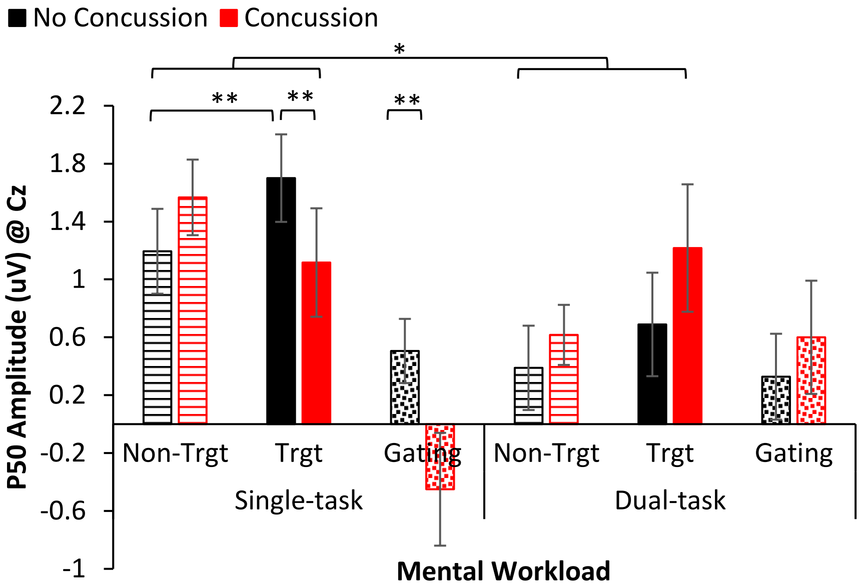
Note. Target (No Concussion (NC) = black solid; Concussion (C) = red solid) and non-target tones (No Concussion (NC) = black dashed; Concussion (C) = red dashed) separated by workload and electrode [**A)** Fz; **B)** Cz; **C)** Pz].

P50 early sensory processing

The three-way mixed model ANOVA (concussion history, task condition, and tone type) was significant F (1, 28) = 5.62 $P = 0.025$, $\eta^2 = 0.016$. A Tukey-Kramer post hoc showed larger P50 ERP target amplitudes in the no concussion compared to the concussion group in the single-task. In addition, target amplitudes were larger than non-target amplitudes in the single-task in the no concussion group whereas the concussion group had no difference between target and non-target amplitudes in the single-task (Figure 3.5). There were no significant differences between the groups or tone type amplitudes in the dual-task. In addition, a main effect of task condition was present F (1, 28) = 10.27 $P = 0.003$, $\eta^2 = 0.075$ showing larger P50 ERP amplitude in the single-task compared to the dual-task. No other effects were significant. The two-way ANOVA on P50 sensory gating showed a concussion history by task condition interaction F (1, 28) = 5.62 P = 0.025, η^2 = 0.083. A Tukey-Kramer post hoc showed that the concussion group had poorer sensory gating (i.e., anti-gating) in the single-task condition compared to the no concussion group and the dual-task condition (Figure 3.5).

Figure 3.5

P50 amplitudes and gating difference



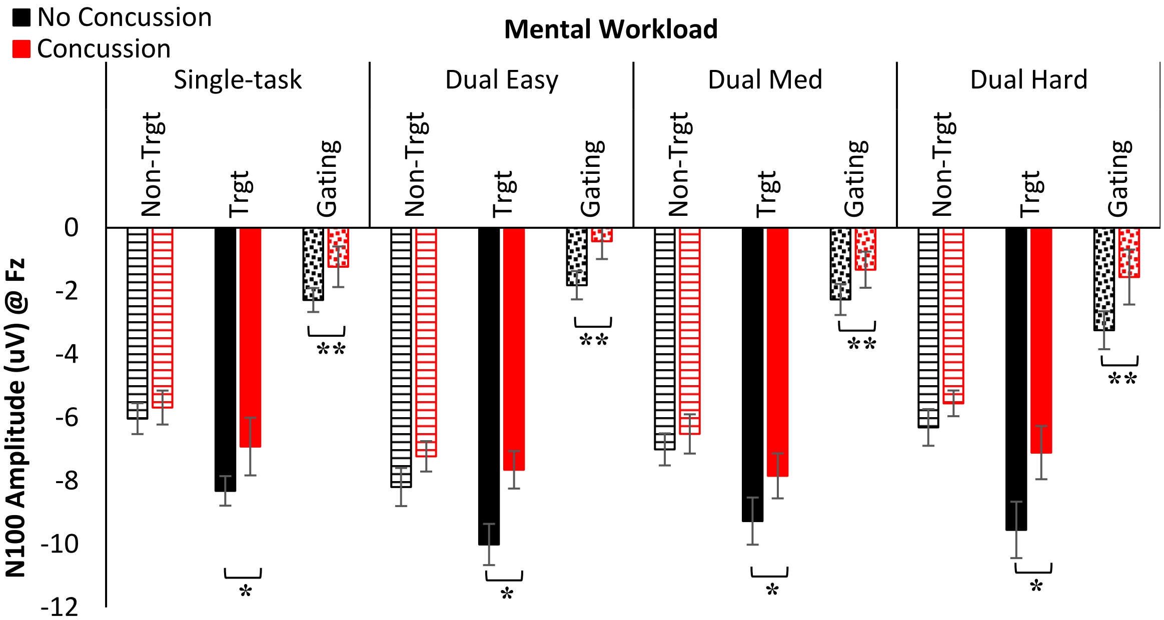
Note. P50 amplitude obtained from electrode Cz plotted by task condition. Target and non-target amplitudes were smaller in the dual-task compared to single-task (*). The concussion group had poorer P50 gating in the single-task compared to the no concussion group (**) but achieved similar gating in the dual-task condition.

N100 late sensory processing

The three-way mixed model ANOVA on N100 ERP amplitude using independent variables concussion history, mental workload (single, dual easy, dual medium, dual hard), and tone type showed a concussion history by tone type interaction F (1, 28) = 6.61, P = 0.016, η^2= 0.012 (Figure 3.6). A Tukey-Kramer post hoc showed larger target tone amplitudes compared to non-target tones for both groups; however, the concussion group had significantly smaller target tone amplitudes compared to the no concussion group (Figure 3.6). The main effects of tone type and mental workload were significant F (1, 28) = 52.30, $P < 0.001$, $\eta^2 = 0.098$ and F (3, 84) = 7.78, $P < 0.001$, $\eta^2 = 0.041$, respectively. A comparison of the means showed target tone amplitudes were larger than non-target tones. A Tukey-Kramer post hoc showed smaller N100 ERP amplitude in the single-task compared to the dual easy and dual medium workloads, and the dual hard had smaller amplitudes compared to the dual easy workload. No other effects were present. The two-way mixed ANOVA on sensory gating showed a significant effect of concussion history F (1, 28) = 6.61, $P = 0.016$, $\eta^2 = 0.076$ indicating that the concussion group had lower gating compared to the no concussion group regardless of workload.

Figure 3.6

N100 amplitude and gating difference



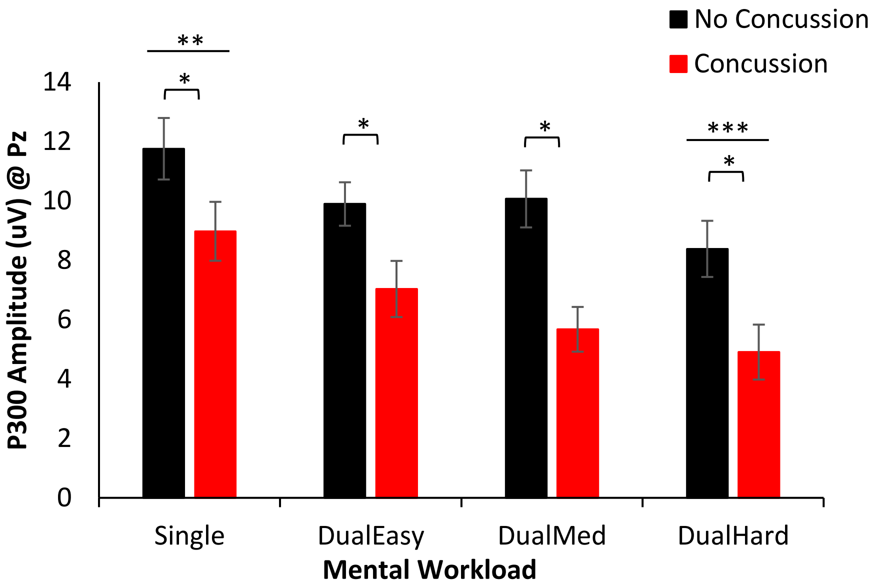
Note. N100 amplitude obtained from electrode Fz plotted as a function of mental workload. Target tone amplitudes were larger compared to non-target tones for both groups but the concussion group had a smaller target tone amplitude compared to no concussed group (*). This resulted in a smaller gating difference for the concussion group (**).

P300 cognitive processing

The two-way mixed model ANOVA on P300 target amplitude using concussion history and mental workload (single, dual easy, dual medium, dual hard) as independent variables showed a significant main effect of concussion history F (1, 28) = 7.73, $P = 0.009$, $\eta^2 = 0.161$, and mental workload F (3, 84) = 19.75 $P < .001$, $\eta^2 = 0.102$ (Figure 3.7). A comparison of the means revealed those with a history of concussion had smaller P300 amplitude across all workloads compared to those without a concussion. A Tukey-Kramer post hoc showed the P300 ERP amplitude was largest in the single-task and smallest in the dual hard workload but no differences were present between the dual easy and dual medium workloads.

Figure 3.7

P300 target tone amplitude



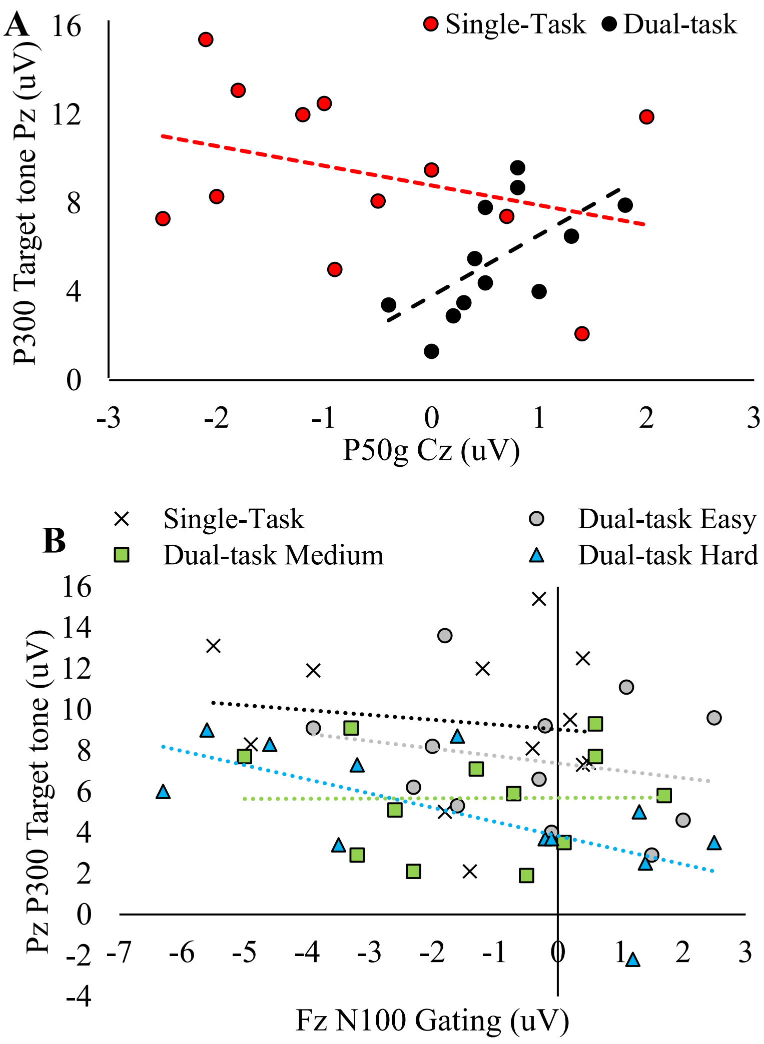
Note. P300 target tone amplitude obtained from electrode Pz. The no concussion group had significantly larger amplitudes than asymptomatic group across workload conditions (*). The single-task had the largest amplitudes (**) whereas the dual hard workload had the smallest amplitudes (***) compared to all other workloads.

Association between sensory and cognitive ERPs

We explored whether sensory gating processes (P50, N100) were related to cognitive processing stages in the asymptomatic group. A Pearson product correlation analysis was performed using P50 and N100 gating values and P300 target amplitude for each workload (single, dual easy, dual med, dual hard for N100 and P300) and task condition (single, dual for P50 and P300). Results showed a significant positive correlation between P50 gating and P300 amplitude in the dual-task r(11) = .62 (95% CI = 0.07, 0.88), p = 0.031 (see Figure 3.8a), which might indicate that individuals with more efficient sensory gating also have more attentional resources to perform the task at the later cognitive stages of information processing. This association did not reach significance in the single-task condition r(11) = -0.352 (95% CI = -0.77, 0.278), p = 0.261. In addition, there was a significant negative correlation between N100 gating and P300 amplitude in the dual hard workload r(11) = -0.648 (95% CI = -0.89, -0.118), p = 0.022 (see Figure 3.8b). The association did not reach statistical significance in the single-task r(11) = -0.109 (95% CI = -0.642, 0.495), p = 0.736, dual easy r(11) = -0.464 (95% CI = -0.819, 0.149), p = 0.128, or dual medium r(11) = 0.007 (95% CI = -0.569, 0.578), p = 0.981.

Figure 3.9

Association between sensory gating and P300 target amplitude in the asymptomatic group



Note. A) P50 gating separated by task condition (single, dual). B. N100 gating separated by workload (single, dual easy, dual medium, dual hard).

3.4 DISCUSSION

Our results replicated previous behavioural findings (Tapper et al., 2017) showing persisting cognitive deficits when mental workload increased in individuals with a history of concussion who are asymptomatic. In particular, the asymptomatic group had a higher percentage of errors (target accuracy) on the auditory oddball task when it was performed simultaneously with the eCorsi task; however, no group differences were present when each task was performed alone. In addition, auditory errors of commission and auditory response times were longer in the asymptomatic group across task conditions. Individuals with a history of concussion showed changes in both sensory and cognitive ERPs as a function of task condition and mental workload. Specifically, the asymptomatic group showed no P50 ERP sensory gating when the oddball task was performed alone but were able to efficiently gate information similarly to their non-concussed counterparts during the dual-task condition, which appears to be driven by better non-target inhibition. In addition, N100 sensory gating was smaller in the asymptomatic group across all workloads, reflected by poorer facilitation of the relevant target tone (i.e., less negativity). At the cognitive stages of information processing, asymptomatic participants had smaller P300 target amplitudes across workload conditions. These findings are consistent with other studies (Bernstein, 2002; Broglio et al., 2009; De Beaumont et al., 2006; Duncan et al., 2003; Gosselin et al., 2006; Rousseff et al., 2006; Segalowitz et a., 2001) suggesting a major consequence of a concussion is either a reduction in the amount of attentional resources available or difficulty in properly allocating attention at cognitive stages of information processing. A novel finding was that individuals who gated information more efficiently at the early, sensory stage (i.e., P50 ERP) may have more attentional resources or allocate them better to perform the task at cognitive stages of information processing.

The current findings demonstrate a deficit in neurocognitive functioning in individuals with a history of concussion who are asymptomatic, reflected in electrophysiological changes in sensory and cognitive information processing. Our findings are consistent with previous studies showing persistent cognitive deficits in individuals who experienced their last concussion months to years prior when performing two tasks simultaneously compared to alone (Bernstein, 2002; Howell, Buckley, Lynall, & Meehan, 2018; Howell et al., 2013; Segalowitz et al., 2001; Tapper et al., 2017). One explanation is that those with a history of concussion have underlying problems in the central executive component of Baddeley's working memory model, which acts as a supervisory control system to coordinate the flow of information to two underlying slave systems and is responsible for directing and prioritizing attention to a given task. Importantly, dual-task paradigms have been used as a means to directly test the central executive system (Della Sala, Baddeley, Papagno, & Spinnler, 1995) and these experimental designs appear to be helpful in discriminating between groups with a history of concussion compared to those without (Bernstein, 2002; Howell et al., 2018; Howell et al., 2013; Register-Mihalik et al., 2013; Segalowitz et al., 2001; Tapper et al., 2017). Interestingly, groups rarely differ in performance when each task is performed alone (i.e., single-task). For instance, previous research in our lab showed no differences in working memory capacity between groups when the eCorsi task was performed alone (Tapper et al., 2017). This finding is consistent with other literature using the N-back task (Dettwiler et al., 2014; Ozen et al., 2013; Thériault, De Beaumont, Tremblay, Lassonde, & Jolicoeur, 2011). Therefore, the tasks the appear to be the most sensitive in discrimintating between groups place a greater demand on the central executive using a dual-task approach.

No research to our knowledge has examined the early, sensory stages of information processing using the auditory oddball task in individuals with a history of concussion. We found no evidence for P50 sensory gating in individuals with a history of concussion in the single-task condition but this gating effect was present and similar to the no concussion group in the dual-task condition. It is possible that the P50 ERP reflects a hard-wired sensory gating mechanism that is automatically activated in the control group; in contrast, individuals with a history of concussion can only activate this mechanism when workload increases and more attentional resources are needed or allocated towards the task in an attempt to maintain performance. Thus, the anti-gating effect shown in the asymptomatic group when the auditory task is performed alone may reflect damage to a sub-cortical area or the neural pathways that connect these areas, which is not recruited when workload is low. This single-task finding is consistent with previous studies showing poorer or even reversed sensory gating (i.e, anti-gating) in participants with mild to severe TBI (Arciniegas et al., 2000) or those with schizophrenia (Yee et al., 2010) when passively listening to the paired click paradigm compared to controls. Interestingly, Yee et al., (2010) found that schizophrenia participants could achieve similar P50 sensory gating ratios as the control group when instructed to attend to the first click in the paired click paradigm. In addition, both groups (controls, schizophrenia) could reduce the P50 gating ratio (i.e., less gating) by attending to the second click. They suggested that the P50 ERP reflects an automatic sensory gating mechanism in healthy controls during passive listening conditions; however, those with schizophrenia can only activate this gating mechanism by voluntarily directing attention to the task. Similar findings were reported by Guterman and colleagues (1992), who showed reduced or reversed sensory gating in healthy participants when attention was directed towards the second stimulus in the paired click paradigm. Taken together, Yee and Guterman’s results provide supporting evidence that the P50 ERP reflects an automatic sensory gating mechanism that can be influenced by attention and this network appears to be compromised following neurological injury (i.e., TBI) or disease.

Research into the neural mechanisms contributing to the P50 sensory gating effect have found the hippocampus to be a main contributor to the P50 gating response in healthy controls

(Boutros et al., 2013; Korzyukov et al., 2007; Williams et al., 2011). In addition, the DLPFC contributed to the P50 response but to a lesser degree. In contrast, only the DLPFC was associated with P50 gating in schizophrenia patients whereas the hippocampus did not contribute to gating (Williams et al., 2011). This is consistent with the view that schizophrenia patients (Williams et al., 2011) and those with a history of mild to severe TBI (Arciniegas et al., 2000, 2001; see review by Girgis, Pace, Sweet & Miller, 2016; Terpstra, Girard, Colella, & Green, 2017) have poorer sensory gating and smaller hippocampal volumes compared to healthy controls. While speculative, our results suggest that those with a history of concussion have damage to neural areas involved in sensory gating including the superior temporal gyrus, hippocampus, thalamus or DLPFC, or dysfunctional connectivity between these structures resulting in poorer sensory gating in the lowest workload condition (i.e., single-task). This explanation is consistent with research showing that those with a history of concussion have underlying damage to the DLPFC which plays an important role in sensory gating (Boutros et al., 2013; Korzyukov et al., 2007; Williams et al., 2011) and encoding visual items into working memory (Bor, Duncan, Wiseman, & Owen, 2003; Ester, Sprague, & Serences, 2015; Santangelo & Bordier, 2019). Interestingly, when mental workload increased (i.e., dual-task), and more attention was needed to perform the task, a normal gating effect was evident in those with a history of concussion. This might be a compensatory effect where more neural resources are recruited in the DLPFC when workload increases (Dettwiler et al., 2014). Another possibility is that gating is achieved through a thalamocortical network that compensates for potential damage to the hippocampus (Papesh et al., 2019), which is reduced in volume following a TBI (Arciniegas et al., 2000, 2001; Misquitta et al., 2018). Again, this thalamocortical network may only be recruited when workload increases. As a result, our findings provide further support for persisting damage to a cortical-subcortial network responsible for early, sensory processing following a concussion.

Research into the later, sensory stages of information processing in individuals with a history of concussion has shown mixed results (Bernstein, 2002; Broglio et al., 2009; De Beaumont et al., 2006; Gosselin et al., 2006; Rousseff et al., 2006; Segalowitz et a., 2001). Our findings show poorer N100 ERP sensory gating across mental workloads in individuals with a history of concussion compared to those without a concussion. This finding is consistent with previous studies reporting smaller N100 amplitudes to auditory target tones in those with a history of concussion compared to their non-concussed counterparts (Duncan et al., 2003, 2005; Gosselin et al., 2006; Ruiter et al., 2019). Importantly, these sensory gating problems may contribute to the longer response times in the concussed group across workloads because these participants had difficulty discriminating target from non-target stimuli. In the single-task condition, this can be compensated for at the cognitive stages of information processing resulting in comparable accuracy between the groups. However, when mental workload increases, poorer facilitation of target tone stimuli may cause more sensory/perceptual noise affecting decision-making processes and resulting in more errors. A similar finding was reported by Adams et al., (2020) who found impaired N70 gating in individuals with a history of concussion due to poorer facilitation of a relevant tactile stimulus that was presented simultaneously with an irrelevant tactile or visual stimulus. Interestingly, their concussion group showed a greater behavioural cost when judging the amplitude of the target stimulus compared to controls suggesting a disruption in early sensory processing negatively affecting behaviour following a concussion. The reduction in N100 target amplitude could be the result of damage to the prefrontal or temporal auditory ERP generators, or the fiber tracts that connect these areas. On the other hand, the reduced N100 amplitude could be the result of a compromised thalamocortical gating mechanism where fewer attentional resources are available to facilitate relevant information (Näätänen & Picton, 1987). This finding would support the hypothesis that the N100 reflects an attentive neural mechanism responsible for gating in relevant information rather than gating out irrelevant stimuli.

The findings of smaller P300 target amplitude in individuals with a history of concussion are consistent with those previously reported using the auditory oddball task (Bernstein, 2002; De Beaumont et al., 2009; Gosselin et al., 2006; Ruiter et al., 2019; Segalowitz et al., 2001). The reduction in P300 ERP amplitude may be the result of poorer allocation of attentional resources (Kahneman, 1973; Kasper et al., 2014; Parasuraman, 1985; Polich, 2007; Singhal et al., 2002; Solis-Marcos & Kircher, 2019; Ullsperger et al., 2001; Watter et al., 2001; Wickens, 2002), reduced decision making abilities (O'Connell et al., 2012) or worse memory updating (Gevins & Smith, 2000). Most studies showing reduced P300 amplitude in previously concussed participants failed to find differences in accuracy and response time measures when the oddball task was performed alone compared to controls (Bernstein, 2002; De Beaumont et al., 2009; Gosselin et al., 2006; Ruiter et al., 2019; Segalowitz et al., 2001). In contrast, studies reporting decreased response accuracy and smaller P300 amplitudes in individuals with a history of mild head injury have identified these differences when participants perform the auditory oddball task simultaneously with a visual number counting task (Bernstein, 2002; Segalowitz et al., 2001). Similarly, we found smaller P300 amplitudes in all workload conditions but response accuracy deficits were only present when participants performed the oddball task simultaneously with the Corsi task. This finding might suggest that those with a history of concussion can compensate when workloads are low to achieve a similar level of performance as their non-concussed counterparts but when demands increase, the ability to properly allocate attentional resources, make a decision or update memory is diminished resulting in a clearer discrimination between those with and without a history of concussion. Interestingly, previous research has shown the P300 amplitude to be positively associated with memory performance (Kramer & Strayer, 1988). Specifically, P300 amplitude was significantly reduced in athletes who suffered a sports-related concussion more than 30 years prior and experience poorer neuropsychological performance compared to controls (De Beaumont et al., 2009). Thus, it would be interesting to follow up with the participants in this study as they age to assess whether they develop more severe cognitive impairments.

3.5 CONCLUSION

The current study showed persisting neurocognitive deficits in asymptomatic individuals with increasing mental workload. Specifically, poorer auditory oddball performance (i.e., lower target accuracy, higher errors of commission) and longer response times were present in asymptomatic individuals when both tasks were performed simultaneously. ERPs showed asymptomatic individuals had poorer sensory gating reflected in smaller P50 and N100 ERP amplitude differences in the single-task condition. In contrast, asymptomatic participants were able to achieve similar P50 sensory gating in the dual-task condition but N100 gating remained lower. As for the cognitive stages of information processing, individuals with a history of concussion had consistently smaller P300 amplitudes suggesting problems in allocating attentional resources, making an accurate decision or updating memory. Together, these findings suggest that more cognitively demanding tasks that increase in mental workload appear helpful in identifying ongoing neurocognitive impairments in individuals with a history of concussion.

Section 4 – *Effects of path configuration on eCorsi performance*

4.1 INTRODUCTION

The clinical management of concussion involves a multidimensional evaluation of symptoms, balance and cognition using computerized neuropsychological tests. Numerous studies have shown these neuropsychological assessment tools provide valid (Barr & McCrea, 2001; Chin et al., 2016; Hecimovich, King, Dempsey, & Murphy, 2018; Maerlender et al., 2010; Ragan, Herrman, Kang, & Mack, 2009; Schatz, 2010; Schatz, Pardini, Lovell, Collins, & Podell, 2006) and reliable (Broglio, et al., 2007; Chin et al., 2016; Elbin, Shatz, & Covassin, 2011; Galetta et al., 2011; Resch et al., 2013) measures for identifying the acute (24h to 72h) and sub-acute (days) cognitive deficits post-concussion. In contrast, a growing body of research suggests that many of these clinical assessments (e.g., symptom checklist, neuropsychological batteries) do not detect any long-term deficits in individuals with a history of concussion (Broglio, Ferrara, Piland, & Anderson, 2006; Iverson et al., 2006; Maerlender et al., 2010). However, it has been shown that dual-task paradigms provide a more sensitive tool to detect lingering cognitive deficits following a concussion (see review by Register-Mihalik et al., 2013). Unfortunately, most of these dual-task paradigms have not seen further investigation into their psychometric properties to understand what factors can influence their performance. As a result, we do not know whether they can be used as a reliable tool by clinicians to identify and manage those who continue to have persisting cognitive deficits. Therefore, the main purpose of this study was to examine the factors that could influence the reliability of one task encompassed in the dual-task paradigm used in previous studies, which is the eCorsi task.

The previous study implemented a dual-task paradigm involving two tasks, including an eCorsi task and an auditory oddball task. The Corsi task has been used in research to examine visuospatial working memory capacity as a function of aging (Beigneux, Plaie, & Isingrini, 2007; Orsini et al., 1987), traumatic brain injury (Fork et al., 2005; Vallat-Azouvi, Weber, Legrand, & Azouvi, 2007), and neurological disease (Grossi, Becker, Smith, & Trojano, 1993; Guariglia, 2007). As a result, the eCorsi task has become part of a clinical computerized psychological assessment tool designed to recognize individuals with a neurological disease/injury and those who are more likely to succeed in occupational, driving and sporting environments (i.e., the Vienna Test System; see review Ong, 2015). Despite its widespread use in clinical and research practice, few studies have investigated the influential factors that can affect performance thereby influencing the estimate of working memory capacity.

Some research has found that manipulating the path configuration characteristics can significantly influence recall performance. A seminal study by Smirni et al. (1983) found that spatial span performance varied based on the set of sequences presented; however, they did not investigate the underlying cause of these differences. Since then, research has identified four factors that can influence recall performance including the number of targets to be remembered (i.e., set size), the number of crossings in a path (i.e., every time a sequence intersects itself), the path length (i.e., total distance of path) and the mean angle of block segments (i.e., the average of all the angles that are present in a sequence when connecting lines between consecutive blocks; Busch, Farrell, Lisdahl-Medina, & Krikorian, 2005; Ginsberg, Rinehart, & Fielding, 2017; Orsini, Pasquadibisceglie, Picone, & Tortora, 2001; Orsini, Simonetta, & Marmorato, 2004; Parmentier, Elford, & Maybery 2005; Smirni et al., 1983). For example, Busch et al., (2005) found reduced trial recall accuracy at set sizes of seven and eight blocks when the path involved three or four crossings compared to zero or one. Similarly, Orsini et al. (2001, 2004) showed decreased recall accuracy when the number of crossings increased from zero to four at set sizes of six and seven. In addition, they found that longer path lengths resulted in poorer recall accuracy compared to shorter lengths. Further research by Parmentier et al., (2005) revealed that the average angle of a sequence could significantly influence recall performance. In particular, participants recalled fewer targets in sequences with smaller (20-40^{o}) compared to larger (60-80^{o}) average angles at a set size of seven. Importantly, they used a different eCorsi procedure where participants were shown black dots that appeared and disappeared one-by-one in sequence and changed location on every trial. They believed that this placed greater load on the working memory system because participants could not use an array to rehearse the presented sequence.

Recent research by Ginsberg et al. (2017) showed that a Corsi pattern could vary in demand by manipulating its angle, number of crossings and path length. Recall performance was studied using low demanding (larger angles, shorter path lengths and no path crossings) and high demanding (smaller angles, longer path lengths with crossings) sequences at set sizes ranging from two to eight blocks. Results showed that recall errors were 13 times higher in the high demand sequences compared to the low demand sequences indicating that changing the path characteristics can significantly influence recall accuracy for sequences at the same set size. One limitation is that they followed the standard Corsi procedures where the test discontinued when two sequences of the same length were recalled incorrectly resulting in fewer participants reaching higher set sizes in the high demand condition compared to the low demand condition. As a result, we do not know if these effects were present at higher set sizes. In addition, they showed high collinearity between pattern characteristics (i.e., more crosses were associated with lower angles and longer path lengths); thus, they could not measure the individual contributions of each factor. In summary, changing the path configuration characteristics can significantly affect the task's ability to provide a valid measure of working memory capacity as the number of path crossings, the path length and the average sequence angle can impose different workloads within the same set size.

Research on the test-retest reliability of the Corsi block task by calculating correlation coefficients has shown mixed results. Studies using the traditional block and board task have reported high test-retest correlations (r = 0.75 – 0.85) when participants performed the task three to 15 days apart (Saggino, Blsamo, Grieco, Cerbone, & Raviele, 2004; Orsini 1994) and moderate correlations (r = 0.46-0.51) at an interval of an average 3.5 years (Lo, Humphreys, Byrne, & Pachana, 2012). In addition, moderate test-retest correlations (r = 0.57-0.61) were reported when participants performed a computerized neuropsychological battery encompassing the eCorsi task that was administered at one-week (White, Forsyth, Lee, & Machado, 2018) and four-week (Williams et al., 2005) intervals. Research evaluating the reliability of the eCorsi task by comparing spatial span performance between the traditional and computerized versions has also reported mixed results (Brunetti, Del Gatto, & Delogu, 2014; Claessen et al., 2015; Nelson, Dickson, & Banos, 2000; Robinson & Brewer, 2016). For example, Robinson et al. (2016) asked participants perform the Corsi task using the traditional version and on an iPad. They reported a low correlation coefficient (r = 0.39, p<.01) for spatial span between the two versions. Research by Brunetti et al. (2014) compared participants spatial span on an iPad to four normative data sets collected using the traditional method (Kessels et al., 2000, 2008; Nelson et al., 2000; Smyth and Scholey, 1994; Vandierendonck et al., 2004). They found no significant differences in spatial span between their participants and the normative data suggesting that computerized versions offer a safe substitute for the traditional version. In contrast, a study by Claessen et al. (2015) reported significantly higher spatial span using the traditional version compared to a tablet version (iPad 3) when tested in the same cohort. The authors suggested that computerized versions might alter the underlying theoretical concepts of the task because participants do not observe the experimenter touching the blocks, which is thought to create an internal motor repertoire that can be more easily reproduced. This view would suggest that the Corsi task does not solely recruit cortical areas responsible for visuospatial working memory, rather it also involves additional neural substrates responsible for motor priming including mirror neurons in the premotor and posterial parietal cortex. Unfortunately, most of these studies do not mention whether the same sequences were used across administrations; thus, the results between versions (traditional, computerized) may be due to different pattern sequences.

Previous research has identified multiple factors that can influence recall accuracy potentially reducing the Corsi tasks ability to reliably measure working memory capacity. One limitation with previous studies is that working memory capacity was measured using the maximal sequence length recalled (i.e., spatial span) or the number of trials recalled. These scoring methods can be defined as absolute storage scores (i.e., sum of trials where all items were recalled in serial order; Redick et al., 2012) and have been shown to have lower internal consistency compared to partial storage scores such as target accuracy (i.e., the number of items recalled in correct serial order regardless of whether the trial was recalled correctly; Conway et al., 2005; Friedman & Miyake, 2005; Redick et al., 2012). As a result, target accuracy would provide a better method for understanding the factors that influence recall performance. A second limitation is that the Corsi task discontinued when participants failed two consecutive trials at the same set size. We believe it is important to test all set size lengths regardless of accuracy because certain path configurations can alter within-level difficulty resulting in better or worse spatial span performance. A third limitation is that most studies have only manipulated the number of crossings and path length without taking into account the average angle of a sequence. As a result, our knowledge of how the average angle of a sequence affects performance is derived from a single study by Parmentier et al. (2005) who only examined this factor at a set size of seven. Thus, our understanding of how average angle affects recall performance at different set sizes is limited.

Therefore, the present study was conducted to address these limitations by manipulating the average angle of a path crossing and performing the same sequence set using a computer version and phone version within the same testing protocol. The rationale for this experiment came from the background findings from study 1 (see appendix B), which showed that the average angle of a sequence affects recall accuracy at spans of seven and eight. An additional goal of the present study was to test the inter-device reliability of recall accuracy between two devices (computer, phone) for the purpose of using a more portable phone version in future research. We hypothesized that 1) sequences with a smaller average angles will result in poorer recall accuracy compared to sequences with larger average angles and, 2) the phone version will show high agreement with the computer version.

4.2 METHODS

4.2.1 Participants

Seventeen graduate and undergraduate students who participated in varsity or competitive recreational sports volunteered for the study. All participants were screened prior to performing the experiment using a basic visual assessment (acuity and stereoacuity). Participants were removed from this study if they did not have normal to corrected normal acuity (< 0.10 logMAR), stereo acuity <50 seconds of arc, a medical history in one of the aforementioned areas (neurological disorder, affective mood disorder, CVD) or currently taking any medication affecting the central nervous system. Three participants reported a previous medical diagnosis of concussion but were not excluded from this study because this has not been shown to affect working memory performance (Tapper et al., 2017; Study 2). Two participants from studies one and two also participated in the present study. The study's protocol was approved by the University of Waterloo Research Ethics Board Committee.

Table 4.1

Participant Demographics [mean (standard deviation)]

	Male (n=7)	**Female (n=10)**
Age	23.43 (4.04)	21.60 (3.53)
Education	17.00 (3.26)	14.80 (1.62)
Acuity (Log MAR)	-0.1 – 0.0	-0.01 – 0.0
Stereoacuity (sec of arc)	27.85 (18.67)	25.00 (9.42)
Sport Type	Soccer, Ice Hockey, Volleyball, Ultimate Frisbee, Basketball	Rugby, Basketball, Ice Hockey, Soccer
Sport experience	14.00 (4.14)	9.00 (6.45)
Total Symptom score (max = 132)	3.57 (7.29)	7.1 (8.71)

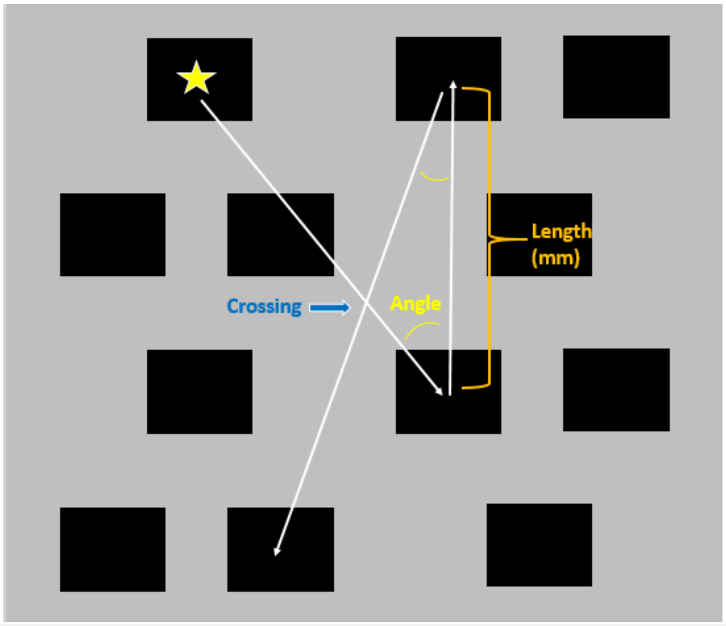
4.2.2 Materials and Procedures

Experimental Design

All participants performed the same blocked design protocol consisting of a single working memory task (i.e., Corsi block task) performed on two devices (computer and phone). The device order was counterbalanced between participants (i.e., 8 participants performed computer version first, followed by the phone version; 9 participants performed phone version first, followed by computer version). Based on the literature review and analysis of data from study 1 (see appendix B), average angle was the main manipulation of interest. Average angle was defined as the angle created when connecting lines between three consecutive blocks and was averaged across the sequence (see Figure 4.1). Corsi patterns were generated with average angles that ranged from 22-94 ° and categorized into three levels of difficulty including, easy = 65-95°, medium = 45-65°, and hard = 20-45°. To avoid common shapes (star, box) and letters (W, Z), we were unable to generate patterns that fixed angle, path crossing and path length; thus, we focused on average angle (see appendix for sequence patterns). The total testing protocol took approximately 25-30 minutes.

Figure 4.1

Path configuration characteristics



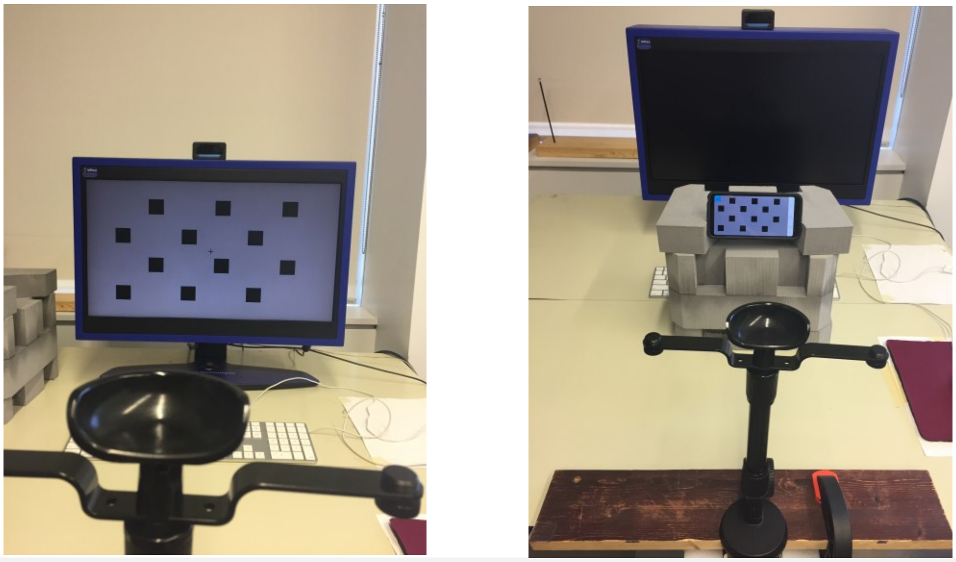
Note. Average angle (yellow), path crossing (blue) and path length (orange) are highlighted in a sample sequence. The yellow star indicates the first target presented in the sequence. White lines are drawn from block to block in consecutive order.

Computer eCorsi

Computer eCorsi block targets were presented and recorded using a custom script written in Vpixx 3.2.1 software. The eCorsi blocks were displayed on a 22.5 inch diagonal display VIEWPixx monitor (resolution 1920x1200 –refresh rate 120Hz) located in quiet laboratory. Participants sat in an adjustable computer chair and were fixed in a chin rest located 90cm from the computer monitor. The experimental protocol began using a modified version of the visuospatial working memory Corsi block test (Corsi, 1973). A fixation cross placed in the center of the screen was surrounded by 12 black blocks (24mm x 24mm) displayed on a grey background (luminance = 92cd/m2; see Figure 4.2). Twelve blocks were chosen to achieve the average angles outlined earlier. Participants were prompted with onscreen instructions to click the central fixation cross to begin the trial. A trial began when one block changed colour from black to white and stayed illuminated for 750ms until the next block in the sequence changed colour. After the sequence was presented, participants were prompted with onscreen instructions to click the blue “Start” box located in the top left corner of the display using a mouse cursor with their preferred hand, and then recall the block sequence in the exact same order in which it appeared. During the encoding and recall phases, participants were free to move their eyes. Two practice trials were performed at set sizes of three and four to familiarize participants with the task. Testing trials involved six sequence patterns, two at each angle of difficulty at block lengths from six to eight blocks. A set size of five blocks had three easy and three hard patterns because this set size was within working memory capacity limits and was not expected to show any differences between pattern difficulties. Patterns difficulties (i.e, easy, medium, hard) were randomly presented at each set size and participants were presented with sequences that progressively increased in set size (i.e., five to six to seven to eight). Participants performed all twenty-four trials (6 trials x 4 levels) regardless of accuracy at lower set sizes.

Figure 4.2

Two digital eCorsi platforms



Note. Computer (left) and phone (right) versions. Viewing distances of 30cm (phone) and 90cm (computer) because the width of the phone screen was approximately 1/3 of the width of the computer screen.

Phone eCorsi

Phone eCorsi block targets were presented using a custom app developed using Android studio software. The blocks were displayed on a 5.76 x 2.94 inch LG G3 screen (resolution 1440 x 2560 -refresh rate 60Hz). A similar experimental protocol was followed as the computer eCorsi task. Participants were fixed in a chin rest located 30cm from the phone that was placed in a holder. The same 12 black block array (12mm x 12mm) was displayed on a grey background. Participants were prompted with onscreen instructions to click the blue “start” button located in the top left corner of the display (see Figure 4.2), which began sequence presentation. After the sequence was presented, participants were instructed to touch the purple “respond” box located in the top left corner of the display using their preferred hand, and recall the sequence by touching the blocks in the exact same order in which they appeared. Blocks illuminated from black to white when a target was selected; thus, the same number of targets needed to be selected corresponding to the set size length before the next trial would begin. Two practice trials at set sizes of three and four were performed to familiarize participants with the task and device. The same 24 sequence patterns (i.e., six trials at set sizes from five to eight) were presented in identical order.

Lastly, participants were asked two questions about their perception of the task following the completion of the experiment: 1) “Not including the number of targets presented, was there anything about the sequences that made them more difficult?” 2) “Was one device harder than the other?” The rationale for these questions was to understand what factors are perceived that make a pattern more difficult for the purpose of incorporating these changes into future studies. In addition, we were interested in whether one device was perceived as more difficult to account for any performance discrepancies between devices.

4.2.3 Data Analysis

Computer eCorsi

The eCorsi block behavioural data analyses were completed using Vpixx 3.2.1 software, Android studio app software and Microsoft Excel (MS Office 2016). For the computerized version, data exported from Vpixx included the X and Y mouse response coordinates. Central fixation was defined as 0, 0 and the X, Y coordinates were measured in millimeters from central fixation. Negative values indicated responses made to the left and below central fixation whereas positive values indicated responses to the right and above fixation. A custom Excel script was developed to identify the participant's target order selection by comparing block location coordinates to the participant's mouse response coordinates. A target was considered correct if the participant's response coordinates fell within the 24mm x 24mm block, and was in the correct order of presentation.

Phone eCorsi

For the phone version each eCorsi block was coded from 1 to 12 resulting in response data reflecting the block number selected. A custom Excel script was developed to identify target accuracy by comparing the block selection number to the correct block number. A target was considered correct it the participant's block number matched the correct order of presentation.

4.2.4 Statistical Analysis

Statistical analyses were performed using SAS Studio software (version 9.04). Descriptive statistics are reported as means and standard deviations. Alpha level was set at 0.05 for post-hoc tests. The Eta squared (η^2) was used to measure effect size, which was calculated using $SS_{BETWEEN}$ divided by SS_{TOTAL} (Levine & Hullett, 2002). The statistical assumption of normality was tested on dependent measure Corsi recall accuracy using the Shaprio-Wilk test and visually inspected using Q-Q plots. The Shapiro-Wilk test did not reach statistical significance ($p > 0.05$) and Q-Q plots showed the data were normally distributed.

First, paired t-tests were performed on target recall accuracy which was conducted to assess the difference in performance between order of device (computer, phone) for the purpose of collapsing data into a single data set. Next, to test the agreement between devices, a Bland-Altman analysis was performed using recall accuracy from each device. A Bland-Altman analysis constructs limits of agreement using an XY scatterplot by calculating the bias, estimated by the mean and standard deviation of the differences between the two quantitative measurements (Giavarina, 2015). The bias is compared to the line of equality (i.e., recall accuracy on both devices is exactly the same) to determine agreement between devices. In addition, correlation coefficient and regression line were used to determine the strength of agreement.

Average Angle

To rule out the effects of collinearity between factors that can influence recall accuracy, two statistical tests were performed to detect multicollinearity including, Variance Inflation Factor (VIF) and examation of the correlation matrix. The VIF was performed on the dependent variable target accuracy, using a multiple regression model with independent factors including, average angle (°), number of path crossings, path length (mm), and number of targets presented (i.e, set size). In addition, a Pearson product correlation was performed on variables average angle, number of path crossings, path length, and set size. A recent review by Dormann et al., (2013) evaluating the methods for identifying collinearity between variables indicated that a VIF value >10 or a correlation coefficient greater than 0.7 can be used to identify multicollinearity between predictor variables. Results showed VIF values less than 3.0 and a significant correlation between average angle and number of path crossings $r(16) = -0.564$, $p < 0.001$ indicating that smaller angles were associated with more crossings; however, this did not reach the 0.7 cutoff threshold; thus, average angle could be used as an independent predictor. Average angle was not associated with set size or path length.

To test the effect of target recall accuracy as a function of average angle, a two-way analysis of variance (ANOVA) was performed on target accuracy using two within-subject factors: average angle (easy, medium, hard) and set size (5 to 8 blocks). Because average angle has been shown to affect target accuracy at set size of seven, we were interested in whether average angle workload differed between set sizes (i.e, how does a hard angle at level 7 compare to an easy angle at level 8). Multiple comparisons were adjusted using Tukey-Kramer when comparing differences between the means.

Pattern difficulty ranking

Previous research has shown that the combination of path angle, crossing, and length can influence recall accuracy (Ginsberg et al., 2017), thus, a method was used to quantify pattern difficulty by ranking sequences from easy to hard using the aforementioned variables (angle, crossing, length). A similar approach was performed by Ginsberg et al. (2017) who categorized sequences as low demanding (few crossings, larger angles, shorter path lengths) or high demanding (larger crossings, smaller angles, longer lengths) at each set size. First, we ordered sequences from 1 to 6 in each category (angle, crossings, length). For example, a pattern could be ordered 1 in the angle category (largest angle) but ordered 3 in the path crossings category (3rd lowest crossings) and ordered 6 in the length category (longest length; see appendix C Table 2). If two sequences had the same number of crossings, they received the same value. This generated three scores (one for each category), which were averaged together to identify the easiest (1 - lowest cumulative score = larger angles, fewer crossings, shorter lengths) and hardest (6 - highest cumulative score = smaller angle, more crossings, longer length) sequences at each set size. To test the effect of pattern workload on target recall accuracy, a two-way ANOVA was performed using independent variables rank (1 to 6) and set size (5 to 8 blocks).

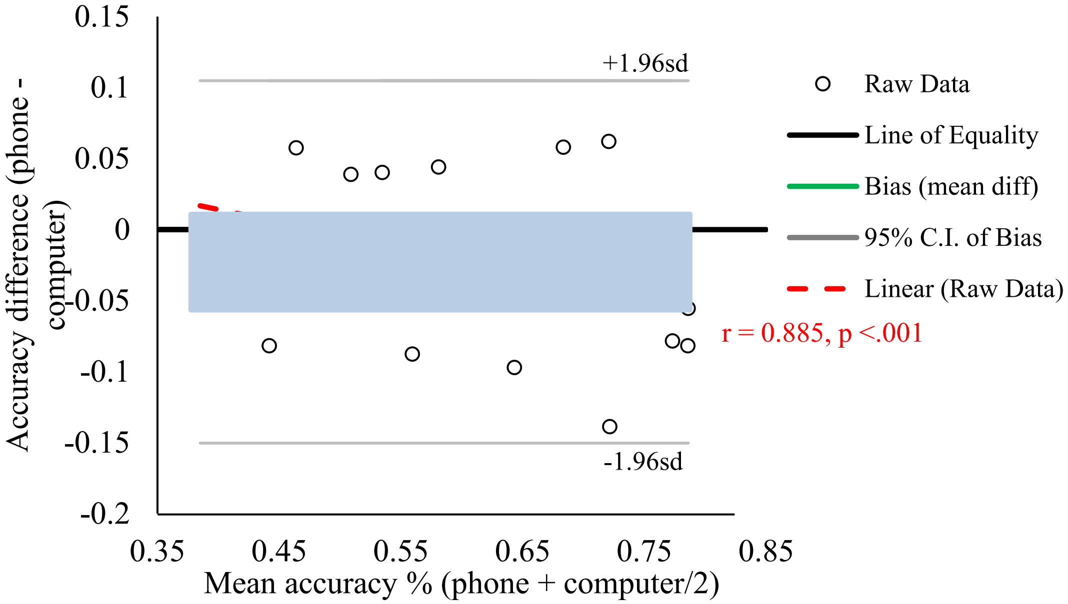
4.3 RESULTS

Assessing agreement between devices

The paired sample t-test on recall accuracy by device confirmed no significant differences in performance between order of devices t (16) = 0.144, p = 0.169; thus, scores were averaged together to test the effect of average angle and sequence rank on recall accuracy. The Bland-Altman analysis is represented in Figure 4.3. Zero on the y-axis represents the line of equality (black line) – the measurements from both devices provide exactly the same results. The bias (i.e., mean difference depicted by a green line) was -2 % accuracy ± 6 (95% CI = 1, -5) indicating that the phone recall accuracy was slightly lower than the computer recall accuracy. Therefore, participants recalled an average of 3.54 ± 10.15 more blocks on the computer device compared to the phone. Since the line of equality lies within the confidence interval of the bias it would suggest that the devices have strong agreement. The correlation coefficient between the two methods was r(16) = .885 (95% CI = 0.704, 0.958), p < .001 and the regression equation was $y = -0.1761x + 0.0846$ (see Figure 4.3)

Figure 4.3

Bland-Alteman analysis of the degree of agreement between devices



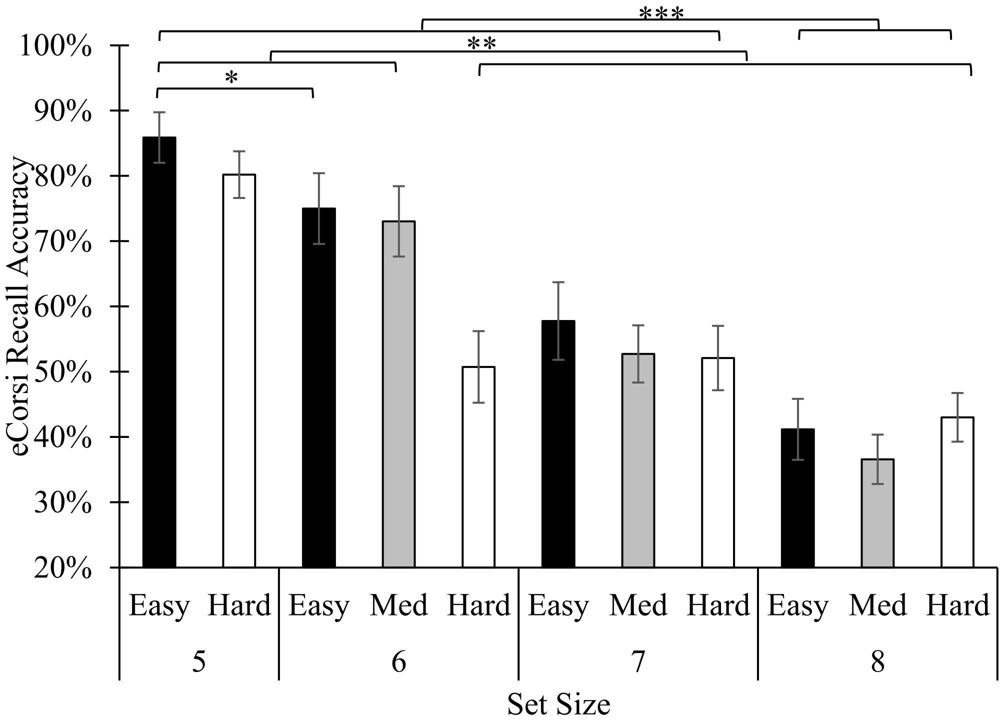
Note. The x-axis represents the mean accuracy of both devices. The y-axis represents the difference in accuracy. The line of equality (black line) represents no difference in recall accuracy between devices. The bias (green line) is calculated as mean difference in recall accuracy between devices; a negative value indicates the phone accuracy was lower than computer accuracy. The 95% C.I. of the bias overlaps with the line of equality suggesting an agreement between devices. All raw data fell within 2sd's of the line of equality.

The effect of average angle

The two-way ANOVA on eCorsi target accuracy performed on the full data set (i.e., both computer and phone accuracy) using independent variables average angle and set size showed significant main effects of average angle F (2, 32) = 10.96 $P < .001$, $\eta^2 = 0.024$, and a set size F (3, 48) = 71.01 $P < .001$, $\eta^2 = 0.395$, and average angle by set size interaction F (5, 80) = 6.14 $P < .001$, $\eta^2 = 0.047$ (see Figure 4.4). A Tukey-Kramer post hoc showed that the average angle of a pattern only affected recall performance at a set size of six. In particular, easy and medium (i.e., average angle 45-65°) patterns at a set size of six had higher recall accuracies compared hard patterns (i.e., average angle 25-45°) a set size of six.

Figure 4.4

eCorsi recall accuracy (represented as the % of blocks recalled)



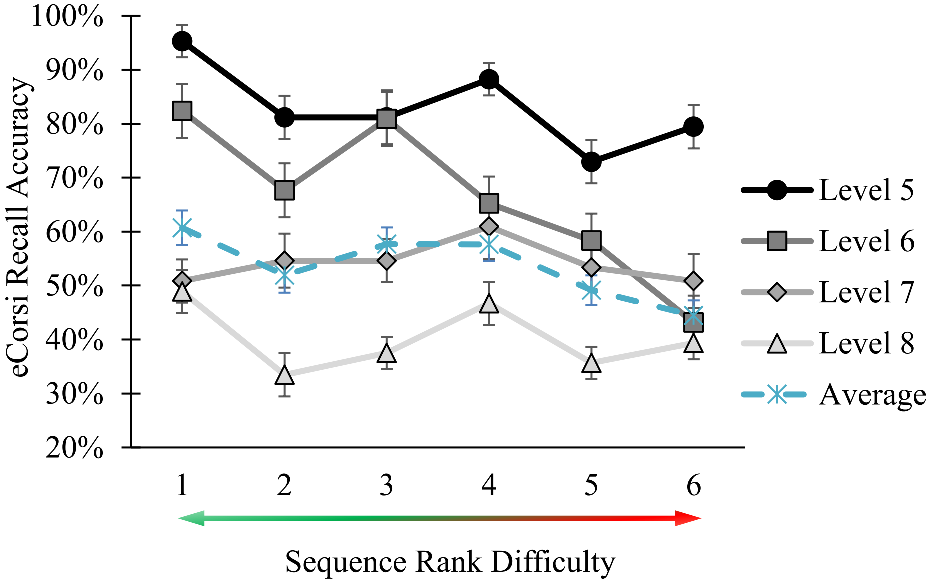
Note. The x-axis is separated by average angle workload and set size. The most evident effect of average angle was at a set size of six where easy and medium angled patterns were recalled better than hard angled patterns.

Pattern difficulty ranking

The two-way ANOVA on eCorsi target accuracy using independent variables sequence rank and set size showed a significant main effect of rank F (5, 80) = 10.36 $P < .001$, $\eta^2 = 0.041$ and set size F (3, 48) = 83.78 $P < .001$, $\eta^2 = 0.321$ and, a rank by set size interaction F (15, 240) = 2.74 $P < .001$, $\eta^2 = 0.046$ (see Figure 4.5). A Tukey-Kramer post hoc showed multiple within and between set size differences. One notable significant differences was that the highest difficulty ranked pattern at a set size of six (i.e., rank 6) was recalled with similar accuracy compared to patterns at a set size of seven and eight.

Figure 4.5

eCorsi recall accuracy as a function of pattern workload



Note. Workload was characterized by ranking sequences from 1 (easy) to 6 (hard) based on their degree of difficulty.

Task questions

Some of the most repeated responses to question 1 (i.e., what makes a sequence difficult?) included targets on the outer edge, the distance between blocks presented, when the sequences crossed back and forth, or if it was an irregular shape. In response to question 2 (which device was harder?), 10 participants perceived the computer to be harder, 3 perceived the phone to be harder, and 4 reported no difference.

4.7 DISCUSSION

The goal of the present study was two-fold. First, we wanted to understand how eCorsi pattern characteristics influence recall accuracy, and second, we tested whether a mobile eCorsi version offers a reliable alternative to assess visuospatial working memory capacity compared to a computer eCorsi version. Our findings showed a decrease in performance when sequences had a smaller average angle compared to a larger average angle. This effect was only present at a set size of six as fewer targets were correctly recalled when the average angle of a sequence was smaller (20-45^o) compared to larger (65-95^o). Interestingly, a smaller angled sequence at a set size of six had comparable recall accuracy as a sequence with a set size of seven. In addition, ranking the sequences according to the three main factors that can influence pattern difficulty (angle, crossings, and length) showed that sequences with lower rankings (i.e., easier patterns) were performed better than higher ranked sequences at set sizes of five and six. The analysis testing the agreement between devices showed little bias between devices as participants recalled an average of three more targets out of a total number of 156 targets on the computer versus phone device. Importantly, recall performance was highly reliable between the devices indicating that a phone can be used as a suitable alternative to measure working memory capacity compared to computerized versions.

The Corsi task has become a widely used tool to assess an individual's visuospatial working memory capacity; however, few studies have investigated how path characteristics can influence recall accuracy (Busch et al., 2005; Ginsberg et al., 2017; Orsini et al., 2001, 2004; Parmentier et al., 2005; Smirni et al., 1983). To our knowledge, no research has examined how the average angle of a sequence affects target recall accuracy at set sizes of five to eight blocks. One study by Parmentier et al., (2005) reported poorer recall accuracy in sequences with more acute angles (i.e, 20-40°) compared to obtuse angles (i.e., 60-80°) but they only tested at a set size of seven. We found this difference to be present at a set size of six as the hard workload sequences (i.e., smaller angles) were recalled more poorly than the easy or medium sequences at the set size length. This effect might only be present at a set size of six because this set size is nearing the maximal working memory capacity while sets of seven and eight exceed maximal capacity. In addition, we found that a hard span of six was comparable in performance to any sequence presented at a set size seven or eight. This is important for two reasons; first, changing the path configuration characteristics can influence the task workload (or perceptual load according to Lavie's theory, Lavie 2005) resulting in better or worse recall accuracy. Second, this might become a significant issue if the eCorsi task is administered using standardized procedures (i.e., two sequences per set size and the task discontinues when two consecutive sequences are incorrectly recalled at the same set size) because a person may achieve a higher score if they receive two easy sequences compared to someone else who received two harder sequences. These findings would suggest that the eCorsi may suffer from reduced parallel forms reliability as two different versions would not result in comparable measures of working memory capacity.

Previous research has shown that the number of path crossings and length of the path can also contribute to the difficulty of a sequence. We attempted to characterize the difficulty of the path sequences created by ranking them based on the angle, crossings and length at each set size. A similar approach was performed by Ginsberg et al., (2017) who found reduced accuracy in high demanding sequences (smaller angles, more crossings, longer length) compared to low demanding sequences (larger angles, fewer crossings and shorter lengths). Similar to their findings, we showed higher recall accuracy in sequences with larger angles, fewer crossings and smaller lengths (rank 1) compared to sequences with smaller angles, more crossings and longer lengths (rank 6). This was most evident at a set size that approaches one's WM capacity limits (i.e., five and six blocks) suggesting that recall performance is significantly influenced by the characteristics of a sequence. As a result, two important methodological modifications should be implemented in future research to make the task more reliable. First, participants should perform all set sizes regardless of accuracy at a lower span because recall errors may be the result of easier or more difficult sequences within a set size. Second, it is important to use similarly demanding sequences when measuring working memory capacity between groups (e.g., between groups or repeated measures) as differences may occur from the requirements of the task (i.e, pattern characteristics) rather than the availability or allocation of resources (i.e., participants characteristics). One possible design modification to measure WM capacity would be to create a psychometric function where the task progressively increases in difficulty within a set size (based on pattern characteristics) before moving on to the next span length (e.g., easy 5 → hard 5 → easy 6 → hard 6…).

Research on the reliability of computerized Corsi block tasks compared to the traditional task has reported mixed results (Brunetti et al., 2014; Claessen et al., 2015; Nelson et al., 2000; Robinson & Brewer, 2016). Three of the four studies reported comparable results between computerized and traditional versions when measuring spatial span and trial accuracy suggesting that computerized versions offer reliable alternatives to the traditional three dimensional block and board CBTT. Our findings using the Bland Altman approach showed little bias between devices because the mean difference fell within the 95% confidence interval of the line of equality, a measure of the difference between devices. An evaluation of the mean and standard deviation of the difference in recall accuracy showed participants recalled approximately three

(±10) more targets on the computer device compared to the phone. This would indicate that participants could recall up to two more trials on the computer platform based on the set size presented (five or eight targets); thus, it appears that there is strong agreement between devices. Further examination of the correlation coefficient showed high association (.885) between devices suggesting that mobile platforms offer a viable alternative for measuring working memory capacity compared to computerized versions. This is important because phones provide an easy method for collecting large-scale studies in a variety of settings. Despite the majority of participants perceiving the phone version to be easier, there was little difference in accuracy between devices. Participants may have perceived the phone to be easier because phones have become more common in people's daily lives; thus, participants may feel more comfortable using this technology. Some participants suggested that the phone was easier because it was more compact, which helped them touch the blocks quicker resulting in an offloading of information stored in WM. Although recall times were not analysed, we would expect shorter response times for the phone version because the blocks are closer together resulting in less travel time between touches. Nevertheless, results from the current study support that mobile platforms provide a practical alternative for assessing working memory capacity using the eCorsi.

Investigations into the neurocognitive mechanisms of working memory have identified a broad network of frontal and parietal cortical areas contributing to the encoding, maintenance and retrieval of items stored in WM. The current study mainly involved the encoding and retrieval of spatial targets because there was no embedded time delay between these two phases (i.e., maintenance phase). Research on the encoding phase has identified greater activation patterns in the attentional network (AN) for trials that were successfully recalled (Bor et al., 2003; Ester et al., 2015; Santangelo & Bordier, 2019). The AN involves frontal and parietal areas including the dorsolateral prefrontal cortex (DLPFC), middle frontal gyrus and superior and inferior posterior parietal cortex. In particular, Bor et al., (2003) examined brain activity using event-related fMRI during the encoding phase of a computerised CBTT involving a 4 x 4 grid of blocks. Pattern workload was manipulated by using "easy," structured sequences - containing familiar shapes (i.e., right angle triangles and parallelograms) – and "hard," unstructured sequences – less symmetry, fewer parallel sides - at a set size of four. Results showed greater target recall accuracy in the structured (easy) versus unstructured (hard) sequences. Both sequence types (easy, hard) showed widespread activity in the AN network during the encoding phase; however, easy sequences had significantly increased activity in the DLPFC, the inferior parietal lobule, and the fusiform gyrus. The authors suggested that the DLPFC facilitates memory by selecting familiar object-based information from the fusiform gyrus an area associated with object perception and recognition (Bar et al., 2001; Gerlach, Law, Gade, & Paulson, 1999), where information can be integrated together into 'chunks'(Bor et al., 2003). Chunking is a memory strategy where items are reorganized into familiar or regular shapes/sequences to create a single-unit rather than separate items (Ericcson, Chase, & Faloon, 1980). As a result, efficiently chunking items reduces the mental workload in the structured sequences (Bor et al., 2003). Our findings showed improved accuracy on sequences with larger average angles, which are similar to the structured sequences used by Bor et al (2003), which could have facilitated more efficient chunking. In contrast, acute angle sequences create less symmetry causing poorer recall accuracy because items cannot be chunked together. In all, our study offers additional insight into the effects of pattern configuration characteristics on the ability to encode and recall visuospatial targets.

4.8 CONCLUSION

The eCorsi is a widely used tool to assess visuospatial working memory capacity; however, changing the average angle of a sequence can significantly influence recall accuracy at a given set size. In particular, sequences with smaller average angles at a set size of six appeared to be more difficult than sequences with larger average angles at a set size of six. In addition, ranking sequences on their degree of difficulty using factors such as average angle, number of crossings and path length may be a potential approach to ensure participants receive sequences with similar workloads. Lastly, mobile platforms appear to offer a reliable method for measuring CBTT performance; thus, can be used in future research to study working memory capacity in a variety of settings and populations.

Section 5 – *Path configuration complexity affects spatial memory span on the Corsi task but does not influence performance of a concurrent auditory discrimination task*

5.1 INTRODUCTION

Working memory is commonly assessed using tasks that progressively vary the number of items that need to be recalled (Cowan, 2016; Redick et al., 2012). For example, the main measure of working memory performance using the Corsi block-tapping task (CBBT) is spatial span, which represents the highest number of items (i.e., set size) that have been successfully recalled in serial order (Berch et al., 1998; Corsi, 1973). Importantly, studies using the Corsi task found that the complexity of a spatial working memory task is not solely dependent on the number of items to be remembered (i.e., set size), rather altering the pattern characteristics within a set size has a significant influence on recall performance (Bor et al., 2003; Busch et al., 2005; Ginsberg et al., 2017; Orsini et al., 2001, 2004; Parmentier et al., 2005; Smirni et al., 1983). Thus, Corsi difficulty can be altered by set size and the complexity of a pattern configuration (i.e., crosses, angles, & distance). However, we do not know whether the load imposed by encoding more difficult patterns is similar to the load imposed by encoding more items or if these two experimental manipulations represent different types of load. Lavie's load theory could provide some insight into this question. Specifically, the theory makes a distinction between perceptual and cognitive load, which have a differential effect on an individual's ability to ignore irrelevant distractor stimuli. In the present study, performance of a secondary auditory discrimination task requires responding to a relevant target while ignoring an irrelevant stimulus, thus, the auditory task could be used to probe the type of load imposed by set size and pattern configuration complexity. It is important to understand the type of load imposed by changing task characteristics because this can help in the development of a valid and reliable task that can be used to discriminate between individuals with and without a history of concussion. Therefore, the goal of the final study was to examine whether manipulating pattern complexity of the primary Corsi block task influences performance on a secondary auditory oddball task.

As mentioned, load theory makes a distinction between two types of workload: perceptual and cognitive. Perceptual load is defined as the amount of information that can be processed in a limited attentional capacity system and it depends on external task-related properties (Konstantinou, Beal, Kin, & Lavie, 2014; see detailed review by Murphy et al., 2016). It is commonly studied by instructing participants to perform a primary visual search task or to encode blocks presented on a display, while ignoring a peripheral distractor stimulus (e.g., superimposed human face or small shape), which is followed by a probe to assess whether the peripheral distractor was processed or not. Research has shown that a higher perceptual load induced by increasing the number of items to be encoded (Burnham, Saba, & Lanngan, 2013; Konstantinou et al., 2014; Konstantinou & Lavie, 2013), increasing the number of incongruent flankers surrounding a target stimulus (Forster & Lavie, 2009), or reducing the discriminability between an object’s features (i.e., size and/or shape) compared to another object (Lavie, Beck, & Konstantinou, 2014), is associated with reduced processing of an irrelevant distractor (Murphy et al., 2016). For example, low perceptual loads are associated with higher accuracy and shorter response times on a primary task and greater sensitivity in detecting a distractor. In contrast, high perceptual loads are associated with longer response times and higher errors rates on the primary task and reduced distractor detection (Murphy et al., 2016). It has been proposed that distractors are more difficult to ignore when the perceptual load of the primary task is low because ‘spare’ attentional capacity is available (or ‘spills-over’) to process a peripheral distractor. In contrast, when perceptual load of the primary task is high, sensory processing capacity becomes bottlenecked such that only relevant information is perceptually processed (i.e., primary task) whereas irrelevant distractors are not processed due to limits in the perceptual capacity (Lavie, 1995). This process is thought to be indicative of more focused attention and early selection.

Cognitive load, referred to as "executive control load," is based on an individual's inherent abilities such as working memory capacity (Lavie, 2005). It is often studied using a "sandwich" task where participants *maintain* a set of verbal items in working memory while ignoring a visual, verbal or tactile distractor or, while simultaneously performing a response-competition task (e.g., responding as quickly as possible to a target letter in the presence of a congruent or incongruent distractors; Dalton et al., 2009; Konstantinou et al., 2014; Konstantinou & Lavie, 2013). The main manipulation of cognitive load involves increasing the number of items to *maintain* in working memory or changing the order of items to be *maintained* (e.g., six digits in ascending order "low load" versus random order "high load"; Dalton, Lavie, & Spence, 2009; Konstantinou et al., 2014; Konstantinou & Lavie, 2013; Murphy et al., 2016). Studies have reported that increasing cognitive load has an opposite effect on distractor processing compared to perceptual load (i.e., increased sensitivity in detecting a peripheral distractor when cognitive load is high) (Dalton et al., 2009; Konstantinou et al., 2014; Konstantinou & Lavie, 2013). These results are thought to be indicative of less focused attention under higher cognitive loads or an impaired prioritization process where distractors compete for processing resources (Murphy et al., 2016). An influential study by Konstantinou et al., (2014) found that increasing the number of colored blocks to be encoded or maintained in working memory reduced processing of a visual distractor whereas increasing the number of verbal items (i.e., letters) to be maintained increased visual distractor processing. This finding suggested that encoding and maintaining items in working memory increases distractor rejection if the tasks share the same perceptual resources (i.e., visuospatial), as reflected in perceptual load; in contrast, when the working memory task involves different resources (i.e., verbal and visuospatial), distractor processing is increased, as reflected in cognitive load. These findings share many commonalities to Baddeley's working memory model, which proposed that performing two tasks within the same slave system (i.e., phonological loop or visuospatial sketchpad) results in performance deficits on one or both tasks whereas performing two tasks from separate slave systems can be done in parallel without affecting the efficacy of either task. However, Baddeley's model makes a clear distinction between tasks requiring working memory maintenance (i.e., slave systems) and tasks requiring executive control (i.e., central executive system) (Baddeley, 2003; Sala, Baddeley, Papagno, & Spinnler, 1995). Nevertheless, the general principle of load theory is whether there is a limitation in the availability of attentional resources (i.e., perceptual load) or a limitation in priority-based control of attentional resources (i.e., cognitive load).

Previous research in our lab showed reduced performance on a secondary auditory task (i.e., lower accuracy, increased errors of commission, and longer response latency) when performed simultaneously during the eCorsi encoding phase (Study 1 & 2; Tapper et al., 2017), and this was further exacerbated (i.e., lower accuracy, and longer RTs) as eCorsi set size increased to high loads (i.e., encoding 7-8 blocks) compared to low (2-4 blocks) and moderate (5-6 blocks) loads (Studies 1 & 2). Our findings are consistent with Baddeley's framework of working memory (Kemps, 2001; Rossi-Arnuad, Pieroni, & Baddeley, 2006; Rossi-Arnuad, Pieroni, Spataro, & Baddeley, 2012; Smyth & Pendleton, 1989, 1990; Vandierendonck et al., 2004). However, previous studies examining dual-task performance during the encoding phase of the Corsi task did not control for path configuration characteristics (Smyth & Pendleton, 1989; Vandierendonck et al., 2004), which has been shown to influence memory encoding and recall

(Bor et al., 2003; Busch et al., 2005; Ginsberg et al., 2017; Orsini et al., 2001, 2004; Parmentier et al., 2005; Smirni et al., 1983), or did not provide specific instruction on what task to prioritize in the dual-task condition (Kemps, 2001; Rossi-Arnuad et al., 2006; Rossi-Arnuad et al., 2012).

Thus, the question remains whether the load imposed by path complexity reflects cognitive or perceptual load. Previous research offers some insight into this question. For instance, Bor et al., (2003) found greater fMRI activation in the DLPFC and better recall performance when participants encoded symmetrical Corsi sequences (i.e., right angled and parallelograms) compared to unsymmetrical sequences (i.e., more crosses, smaller angles). The authors suggested that the increased DLPFC activity facilitated memory encoding by efficiently chunking information together resulting in a reduced cognitive load. Other research has suggested that path complexity imposes a greater load on perceptual processing capacity because perceptually grouping items to conform to the Gestalt principle (i.e., similarity, proximity, continuity, etc.; see review Hurlstone, Hitch & Baddeley, 2014) is dependent on selective attention. Specifically, sequences that are more symmetrical (i.e., follow smooth and continuous trajectories) require less attention to be perceptually grouped together compared to asymmetrical sequences. Therefore, if path complexity affects perceptual load, we would expect worse performance on the secondary auditory task when encoding more difficult sequences because more attention will be required to perceptually process the difficult sequences leaving less available for the auditory task. Alternatively, if path configuration complexity imposes a cognitive load, we would expect no change in auditory task performance because attention would switch to the auditory task due to a limitation in priority-based control of attentional resources

The primary goal of this study was to provide a further understanding of the characteristics of the dual-task paradigm by investigating the type of workload imposed by path complexity. It was hypothesized that increasing path complexity within a set size will increase perceptual load resulting in reduced performance on the secondary auditory oddball task. In particular, oddball accuracy will decrease, errors of commission will increase, and response times will be longer when presented with harder pattern configurations (i.e., more crosses, smaller angles, and longer path distances) compared to easy patterns (i.e., no crossings, larger angles, and shorter distances). A secondary goal of this study was to assess the repeatability of our previous findings which showed that individuals with a history of concussion perform worse in dual-task conditions compared to those without a concussion. Notably, the current study might offer insight into what type of load (perceptual or cognitive) is most sensitive to the long-term effects of concussion.

5.2 METHODS

5.2.1 Participants

Nineteen varsity and competitive recreational team-sport athletes volunteered for the study (see Table 5.1). Before entering the lab, participants performed a modified version of the Waterloo health history questionnaire online using Qualtrics^{XM} and a COVID-19 pre-screening self-assessment, which asked questions regarding symptomology, at risk groups, close or physical contact with anyone diagnosed with COVID-19 or recently travelled. A visual acuity test using a Bailey-Lovie chart was performed in the lab prior to study collection. Participants were removed from this study if they did not have normal to corrected normal acuity, reported a medical history of neurological disorder, affective mood disorders, or cardiovascular disease or, were currently taking any medication affecting the central nervous system. No participant reported any COVID-19 related symptoms, did not fall into an at-risk group, and were not in close/physical contact with anyone who had COVID-19 or had recently travelled. Ten participants reported having a medically diagnosed concussion and were matched for sex, age and sport experience with nine controls who reported no medically diagnosed history of concussion. Two participants (one no-concussion, one asymptomatic) in the present study also participated in studies one and two. A sample size calculation of 12 was calculated based on the significant difference in accuracy between easy and hard patterns at a set size of six from study three. The study’s protocol was approved by the University of Waterloo Research Ethics Board Committee.

Table 5.1

Participant Demographics [mean (standard deviation)]

	No-Concussion		Asymptomatic		
	Male (n=5)	Female (n=4)	Male (n=5)	Female (n=5)	Between groups t-test
Age	26.20 (4.65)	22.20 (2.44)	28.20 (4.21)	24.75 (4.27)	*p* = 0.178
Education					*p* = 0.173
Acuity (Log MAR)	-0.2 – 0.0	-0.2 – 0.0	0.0	0.0	*p* = 0.988
Sport Type	Basketball, Ice Hockey, Volleyball	Basketball, Rugby, Field Hockey	Soccer, Ice Hockey, Football	Soccer, Ice Hockey, Basketball, Rugby	-
Sport experience	18.20 (4.65)	13.54 (3.44)	19.20 (4.96)	13.75 (1.89)	*p* = 0.852
Total Symptom score (max = 132)	3.6 (2.8)	3.5 (4.4)	4.4 (6.2)	7.6 (10.5)	*p* = 0.421
# of Concussions	-	-	1.8 (1.1)	204 (1.7)	-
# of participants Knocked Unconscious	-	-	2	0	-
Time since concussion (mos.)	-	-	66.6 (68.00)	37.4 (10.13)	-

5.2.2 Materials and Procedures

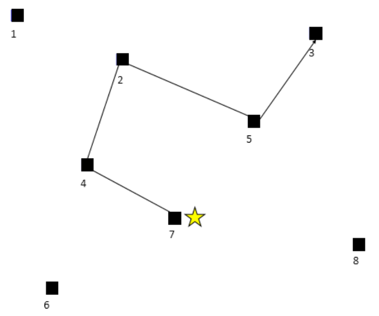
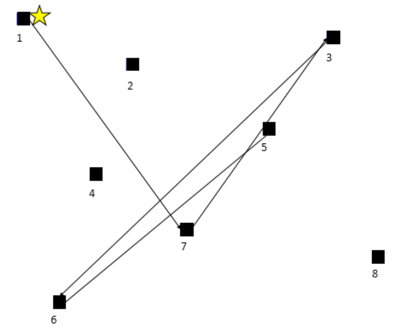
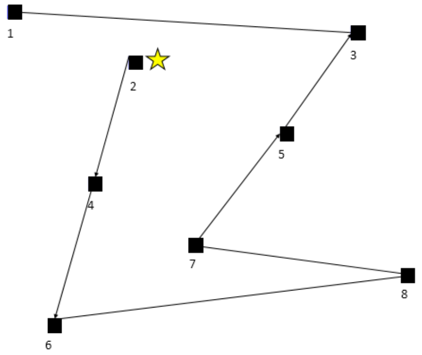
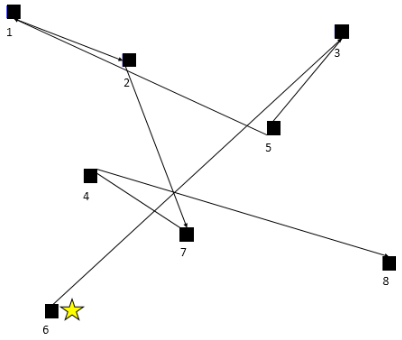
Experimental Design

eCorsi task

The eCorsi was created using VPixx 3.2.1 software and administered on a Macbook Pro laptop (OS X, version 10.8.5). Participants sat comfortably approximately 60 cm from the centre of the laptop screen and were free to make natural head and eye movements throughout the task. The test involved eight black blocks displayed on a grey background, which changed colour from black to white every 750ms in a specific sequence. The goal was to encode and recall all targets in the exact same order in which they appeared. The test began with the participant being shown a sample trial performed by the investigator at a set size of three before practicing the same sequence themselves. Next, four practice sequences were performed at a set size of four blocks to familiarize participants with the progressive increase in set size. The testing condition involved six sequences presented at each set size from five to eight blocks. Each set size had three trials that were categorized as "easy" defined as sequences with no path crossings, an average angle greater than 70 degrees, and "shorter" distances between target blocks presented. Total distances for the easy sequences ranged from a minimum of 255mm (5 blocks) to a maximum of 685 mm (8 blocks). The other three sequences were categorized as "hard" defined as sequences with more than two path crossings, an average angle less than 50 degrees, and "longer" path distances between targets presented. Total distances for the hard sequences ranged from a minimum 530mm (5 blocks) to maximum of 945mm (8 blocks). Distances in the hard sequences were 10-60% longer than the easy sequences within the same set size (see Figure 5.1).

Figure 5.1

Examples of easy and hard patterns

Set size	**Easy**	**Hard**
5		
8		

Note. Easy and hard patterns at set sizes of five and eight blocks. The yellow star indicates the first block presented in the pattern and the lines are connected in sequential order of block presentation.

Auditory oddball task

Auditory tone pips were created using VPixx 3.2.1 software and presented binaurally at 60 decibels using a Macbook Pro laptop (OS X, version 10.8.5). First, participants were presented with an iteration of high (1000Hz) and low (325Hz) tones and asked if they could discriminate between the two tones. All participants responded “Yes”, confirming they could correctly discriminate the two tones. Then, participants were instructed to respond by clicking a computer mouse with their preferred hand as quickly as possible when a high tone was presented (*probability* = 40%), and to withhold a response when a low tone was presented (*probability* = 60%). The testing protocol began with the participant clicking the central fixation followed by an iteration of high and low tones presented at a fixed interstimulus interval of 700ms. Participants were presented with a sample trial performed by the investigator involving a five tone pip iteration (equivalent to level three in the eCorsi task) prior to performing the practice trial. Four tone iterations at level four (i.e., six tones) were used to further familiarize participants with the task. The testing condition involved six trials presented at levels five (7 tones) to eight (10 tones). In every trial, target tones were separated by at least one non-target tone. Of the 204 tones presented throughout the single-task condition, 84 were high tones (target tone) and 120 were low tones (non-target tone). The same three tone iterations presented in the easy sequence condition were presented in the difficult sequence condition within the same set size.

Dual-task

The third testing condition involved performing both eCorsi block and auditory oddball tasks simultaneously. Participants were shown a practice trial performed by the investigator at a set size of three (five auditory tones) before performing the task. Then, participants performed four practice trials at a set size of four (six auditory tones). The trial began by clicking on the central fixation followed by auditory tones presented every 700ms and the eCorsi blocks changing colour every 750ms. Participants had to respond to a high tone and withhold a response to a low tone while encoding the eCorsi sequence and not during Corsi recall. Instructions were given to prioritize the Corsi test in the dual-task condition.

5.2.3 Statistical Analysis

Statistical analyses were performed using SAS Studio software (version 9.04). Descriptive statistics are reported as means and standard deviations. Alpha level was set at 0.05 for post-hoc tests. The Eta squared (η^2) was used to measure effect size, which was calculated using $SS_{BETWEEN}$ divided by SS_{TOTAL} (Levine & Hullett, 2002). The statistical assumption of normality was tested using the Shapiro-Wilk test and visually inspected using Q-Q plots on dependent measures Corsi recall accuracy, auditory accuracy, auditory errors of commission and auditory response time. To test the assumption of homogeneity of variance, Bartlett's test was used.

Effects of pattern complexity on performance

eCorsi task

The Shapiro-Wilk test on Corsi accuracy did not reach significance and Q-Q plots showed the data were normally distributed; thus, parametric tests were used to test hypotheses.

To assess whether participants followed instructions by prioritizing the eCorsi in the dual-task condition, a paired-test was performed on eCorsi recall accuracy between task conditions (single, dual). Results showed no significant difference between task conditions t (18) = 1.66, p = 0.115, indicating participants followed instructions.

To test whether the manipulation of path configuration complexity (easy, hard) was successful, a two-way ANOVA was performed on the percentage of eCorsi targets successfully recalled in the dual-task condition. Two within-subject variables included path complexity (easy, hard) and set size (five to eight blocks). The purpose of only testing the dual-task condition was to determine the imposed load of the eCorsi on auditory task performance. Tukey-Kramer post hoc test was used to compare differences between the means in cases where the main effects or interactions reached significance.

Auditory oddball task

The Shapiro-Wilk test on auditory accuracy and errors of commission were significant ($p < 0.001$) and Q-Q plots showed the data were negatively and positively skewed, respectively. Further inspection of the data showed that accuracy and errors were skewed in both single-task and dual-task conditions. Thus, auditory accuracy and errors of commission were converted to ranks (Conover & Iman, 1981; Conover, 2012; Zhuang et al., 2018) to test hypotheses. Auditory response time was normally distributed; thus, parametric tests were used to test hypotheses.

To assess the effects of dual-tasking on auditory oddball performance, three separate paired t-tests were performed on outcome variables ranks of auditory oddball accuracy (% of target tones correctly responded to), ranks of errors of commission (% of non-target tones incorrectly responded to), and response time (ms; to target tones).

To test auditory performance (ranks of accuracy, ranks of errors of commission, and response time) in the dual-task condition a two-way ANOVA was performed using within-subject factors path complexity (easy, hard) and set size (five to eight blocks). Tukey-Kramer post hoc test was used to compare differences between the means when the main effects or interactions reached significance.

Effects of concussion history on dual-task performance

eCorsi task

The Bartlett's test for homogeneity of variance between groups (no concussion, concussion) did not reach significance ($p = 0.811$); thus, parametric tests were used to test hypotheses.

To test the effects of concussion history on eCorsi performance, a four-way mixed model ANOVA was performed on the percentage of eCorsi targets successfully recalled. Independent variables included one between-subject factor: concussion history (no concussion, asymptomatic), and three within-subject factors: task condition (single, dual), path complexity (easy, hard), and set size (five to eight blocks). Task condition was included to investigate whether there were differences between groups in the single or dual task conditions. Tukey-Kramer post hoc test was used to compare mean differences if there were main effects or an interaction.

Auditory oddball task

The Bartlett's test for homogeneity of variance between groups (no concussion, concussion) did reach significance for auditory accuracy ($p < 0.001$) and errors of commission ($p < 0.001$); thus, auditory accuracy and errors of commission were converted to ranks (Conover & Iman, 1981; Conover, 2012; Zhuang et al., 2018) to test hypotheses.

To test the effects of concussion history on auditory oddball performance, a four-way mixed model ANOVA was performed on outcome measures auditory accuracy (ranked % of target tones correctly responded to), errors of commission (ranked % of non-target tones incorrectly responded to), and response time (to target tones). Independent variables included one between-subject factor: concussion history, and three within-subject factors: task condition (single, dual), path complexity (easy, hard) and set size (six to ten tones). Tukey-Kramer post hoc test was used to compare mean differences if there were main effects or an interaction.

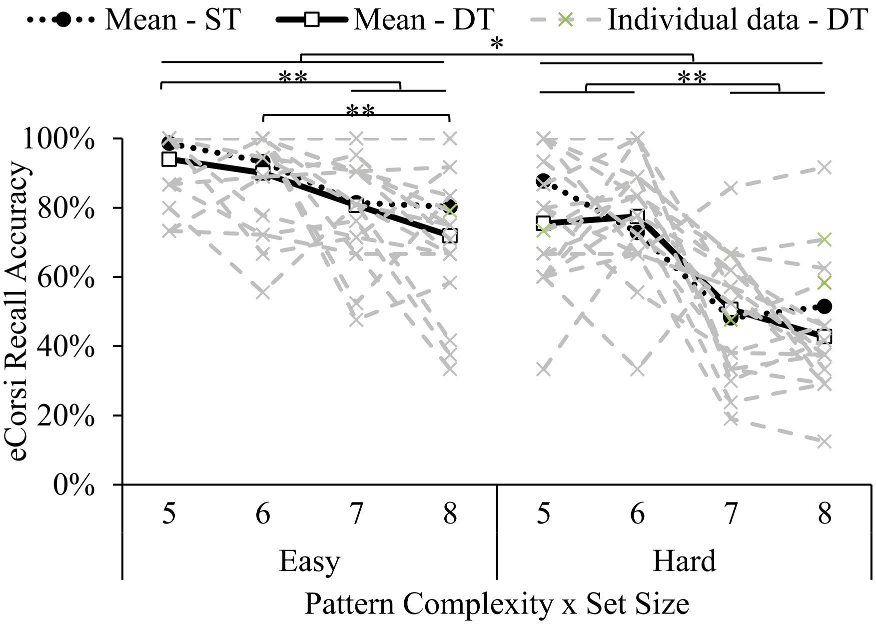
5.3 RESULTS

Effects of pattern complexity on eCorsi test performance

The two-way ANOVA on the percentage of eCorsi targets successfully recalled in the single-task condition revealed a significant main effect of pattern complexity $F\,(1, 18) = 153.79$, $p < .001$, $\eta^2 = 0.271$, and set size $F\,(3, 54) = 36.33$, $p < .001$, $\eta^2 = 0.282$ and, a pattern complexity by set size interaction $F\,(3, 54) = 5.51$, $p = 0.002$, $\eta^2 = 0.036$. Tukey-Kramer post hoc showed a steeper reduction in performance on the hard patterns compared to the easy patterns. In particular, hard patterns at set sizes of five and six were recalled more accurately than hard patterns at set sizes of seven and eight but no significant differences were found in easy patterns between a set size of five and six, six and seven, and seven and eight (see Figure 5.2). The same effects were present in the dual-task condition showing a main effect of pattern complexity $F\,(1, 18) = 122.96$, $p < .001$, $\eta^2 = 0.240$, and set size $F\,(3, 54) = 44.38$, $p < .001$, $\eta^2 = 0.259$, and a pattern complexity by set size interaction $F\,(3, 54) = 3.15$, $p = 0.011$, $\eta^2 = 0.029$. Tukey-Kramer post hoc showed a steeper drop-off in recall accuracy in the hard patterns compared to easy patterns. Specifically, hard patterns with set sizes of five and six were recalled more accurately than hard patterns at set sizes of seven and eight; however, there were no significant differences between a set size of five and six, six and seven, and seven and eight in the easy patterns. Lastly, hard sequences at a set size of five and six were recalled with similar accuracy as the easy sequences at set sizes of seven and eight.

Figure 5.2

Corsi recall accuracy as a function of pattern complexity and set size



Note. The x-axis is separated by pattern complexity (easy, hard) and set size (5 to 8 blocks). The dual-task (DT) group average is shown in the solid black line and individual data in gray dash lines whereas the single-task (ST) group average is shown in the black dotted line.

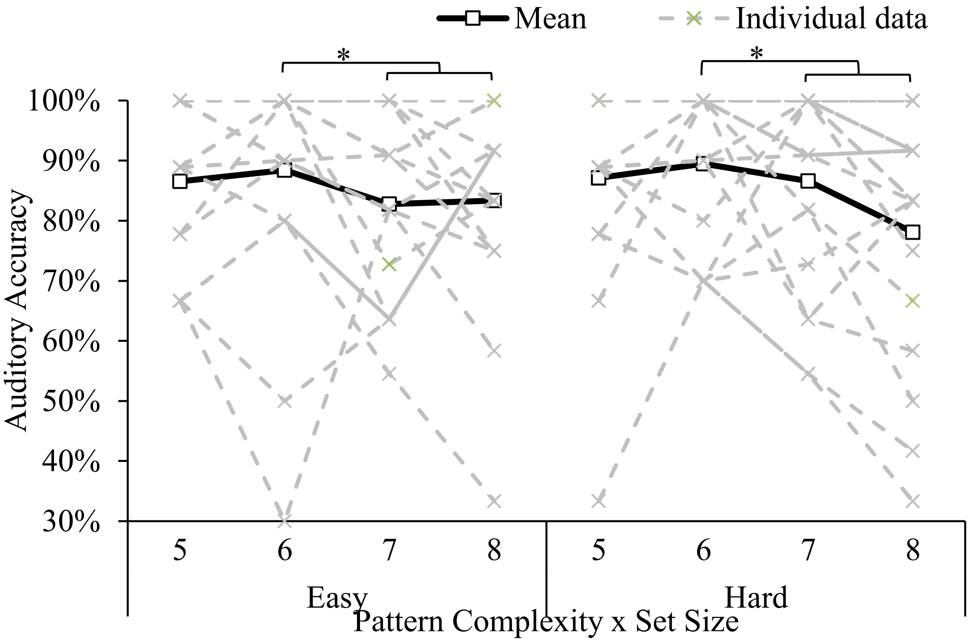
Effects of pattern complexity on auditory oddball task performance

The paired t-tests on auditory measures (ranks of auditory accuracy, ranks of errors of commission, and response time) showed significantly lower accuracy t (18) = 12.17, $p < 0.001$, higher errors of commission t (18) = -5.74, $p < 0.001$, and longer response times t (18) = -9.05, $p < .001$ in the dual-task condition compared to the single-task. This further validated that the auditory task was the secondary task in the dual-task condition.

The two-way ANOVA on the computed ranks of auditory accuracy in the dual-task condition revealed no significant effect of pattern complexity F (1, 18) = 0.23, $p = 0.637$, $\eta^2 = 0.000$, and no pattern complexity by set size interaction F (3, 54) = 1.02, $p = 0.393$, $\eta^2 = 0.012$. This finding supports our alternative hypothesis that the load imposed by pattern complexity reflects cognitive load because secondary auditory oddball accuracy was not influenced by changing eCorsi pattern complexity within a set size (Figure 5.2). There was a significant main effect of set size *F* (3, 54) = 4.25, $p = 0.009$, $\eta^2 = 0.037$. Tukey-Kramer post hoc showed reduced auditory accuracy when presented with set sizes of seven and eight compared to a set size of six. There were no differences between a set size of five compared to six, seven or eight.

Figure 5.3

Auditory accuracy in the dual-task condition

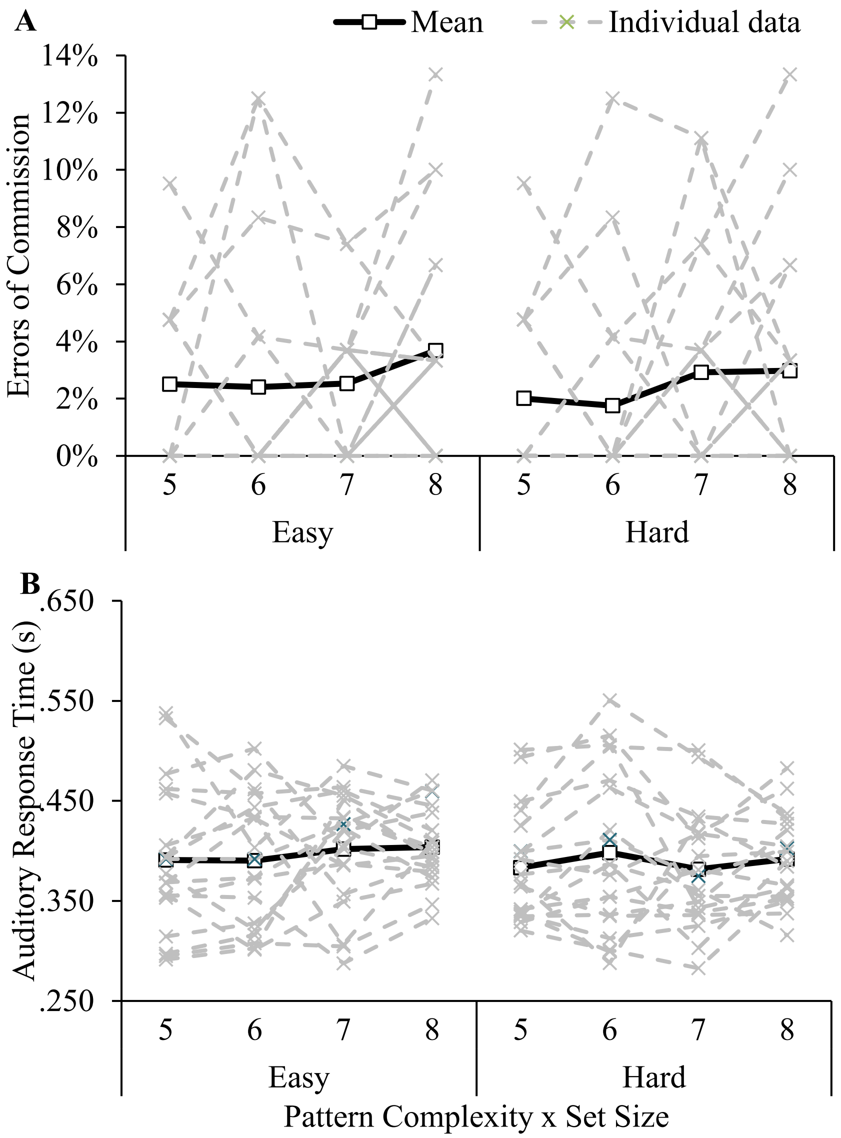


Note. The x-axis is separated by pattern complexity (easy, hard) and set size (5 to 8 blocks). There were no differences in accuracy by pattern complexity but it did decrease as a function of set size (6 > 7 and 8).

The two-way ANOVA on the ranks of auditory errors of commission and on response time in the dual-task condition revealed no significant main effects or interactions ($p > 0.22$ for all effects; see Figure 5.4A and B).

Figure 5.4

Auditory A) errors of commission (%) and B) response time (s) in the dual-task condition



Note. The x-axis is separated by pattern complexity (easy, hard) and set size (5 to 8 blocks). There were no significant effects of pattern complexity or set size on errors of commission or response time.

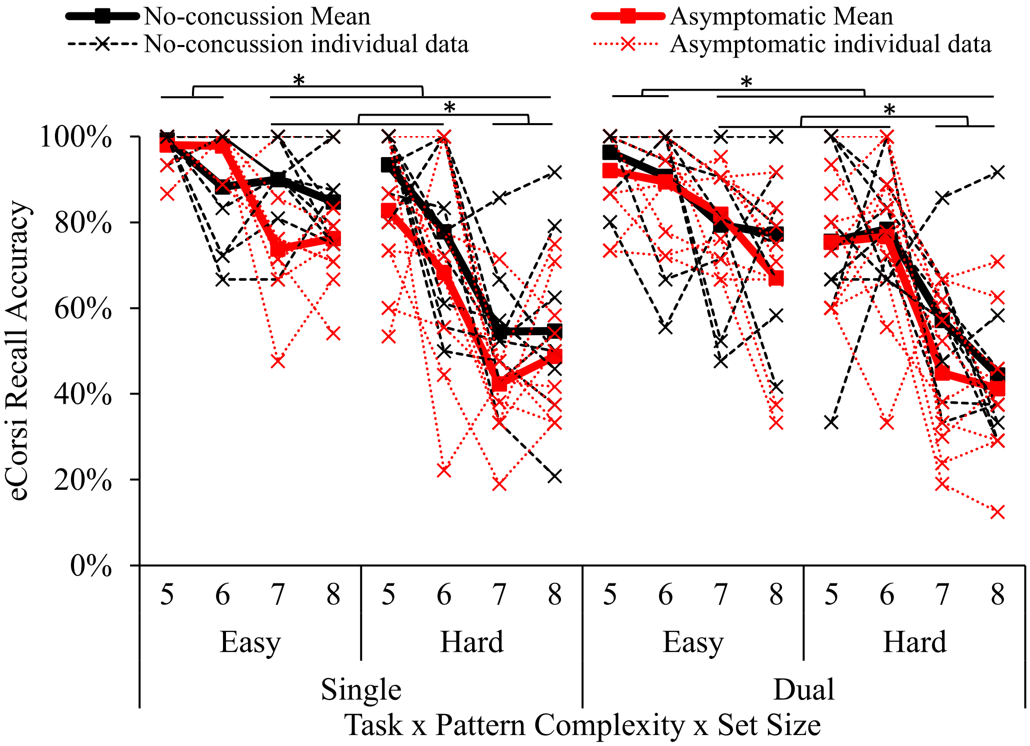
Effects of concussion history on dual-task performance

eCorsi task

The four-way ANOVA on eCorsi recall accuracy revealed a significant three-way concussion history by pattern complexity by set size interaction $F\ (6, 51) = 3.15\ P = 0.011$, $\eta^2 = 0.029$. Tukey-Kramer post hoc showed lower accuracy for hard compared to easy patterns in both groups (no concussion, asymptomatic), and this decreased as a function of set size (5 and 6 blocks > 7 and 8 blocks). In contrast, the no-concussion group had a similar recall accuracy at a set size of six compared to sizes of seven and eight in the easy patterns (see Figure 5.5).

Figure 5.5

Corsi recall accuracy as a function of task condition, pattern complexity and set size



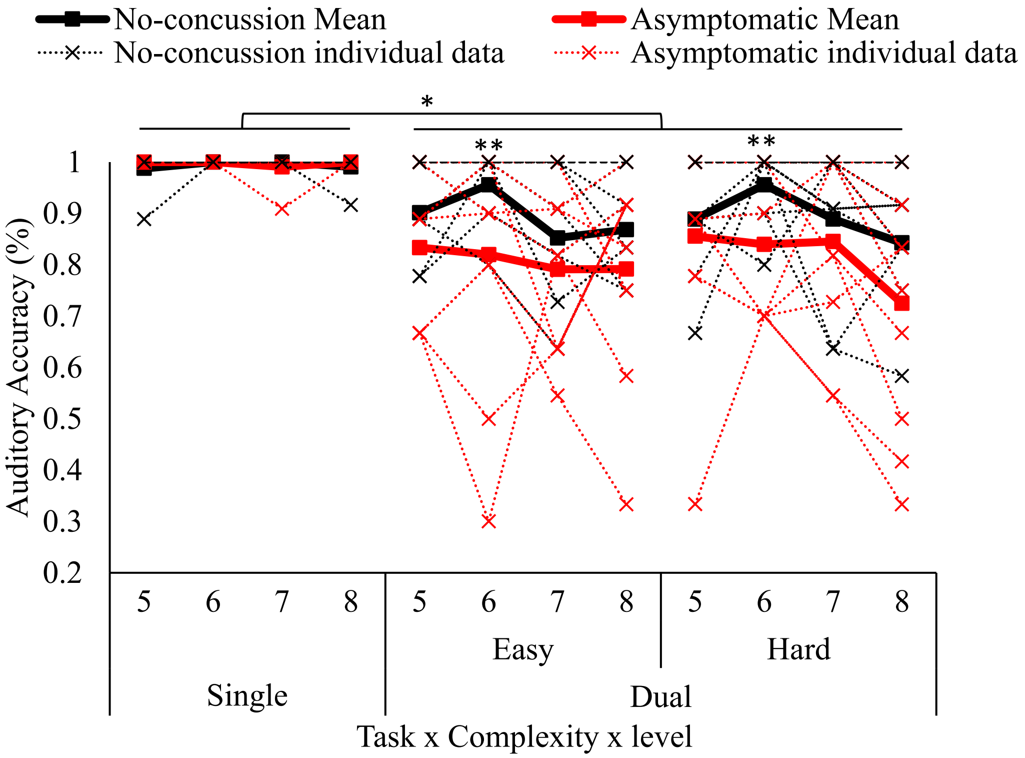
Note. The bold black line represents no-concussion mean whereas bold red line indicates asymptomatc mean. Individual data points are shown in black (no concussion) and red (asymptomatic) dashed lines. Accuracy decreased as a function of set size and pattern complexity.

Auditory oddball accuracy

The four-way ANOVA on auditory accuracy (ranked % of tones correctly responded to) showed a significant three-way concussion history by task condition by set size interaction *F* (6, 51) = 2.58 *P* = 0.029, η^2 =0.017. Tukey-Kramer post hoc revealed that both groups had lower accuracy in the dual-task compared to single-task; moreover, those with a history of concussion had lower accuracy at a set size of six in the dual-task condition compared to the no concussion group but not at sets sizes of five, seven or eight (see Figure 5.6). No significant between group differences were shown in the single-task. No other main effects or interactions were significant.

Figure 5.6

Auditory accuracy (represented as % of tones correctly responded to)



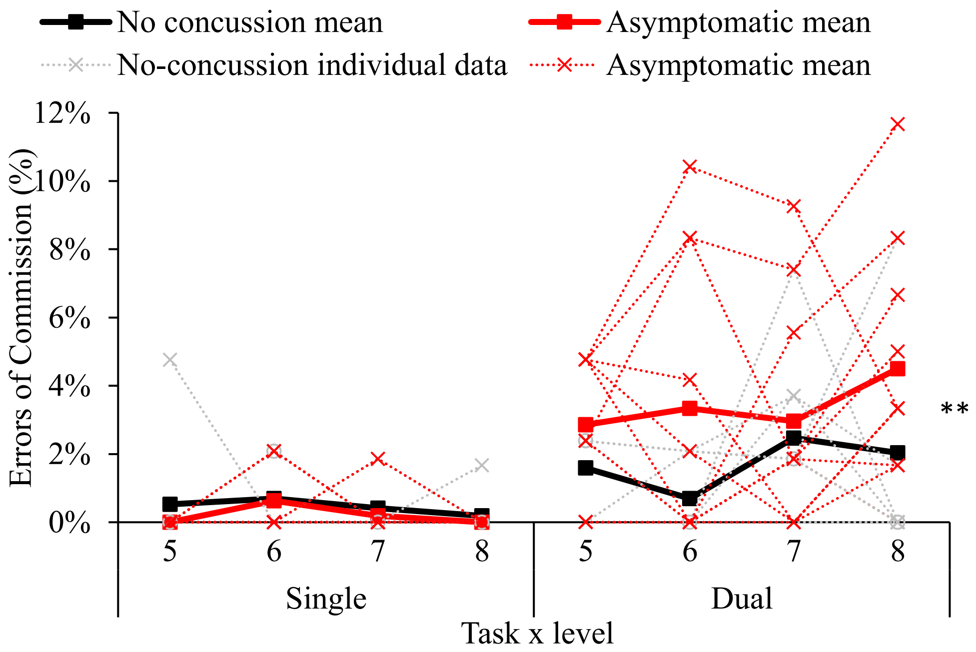
Note. Dual-task accuracy was lower than single task in both groups but the asymptomatic group had lower accuracy at a set size of six in the dual-task compared to the no-concussion group.

Auditory oddball errors of commission

The four-way ANOVA on errors of commission (ranked % of non-target tones incorrectly responded to) showed a significant concussion history by task condition interaction was significant *F* (1, 17) = 4.60 *P* = 0.047, η^2 =0.026 indicaitng those with a history of concussion performed more errors in the dual-task condition compared to those without a concussion (see Figure 5.7). No other concussion related effects reached statistical significance.

Figure 5.7

Auditory errors of commission (% of incorrectly responded to non-target tones)



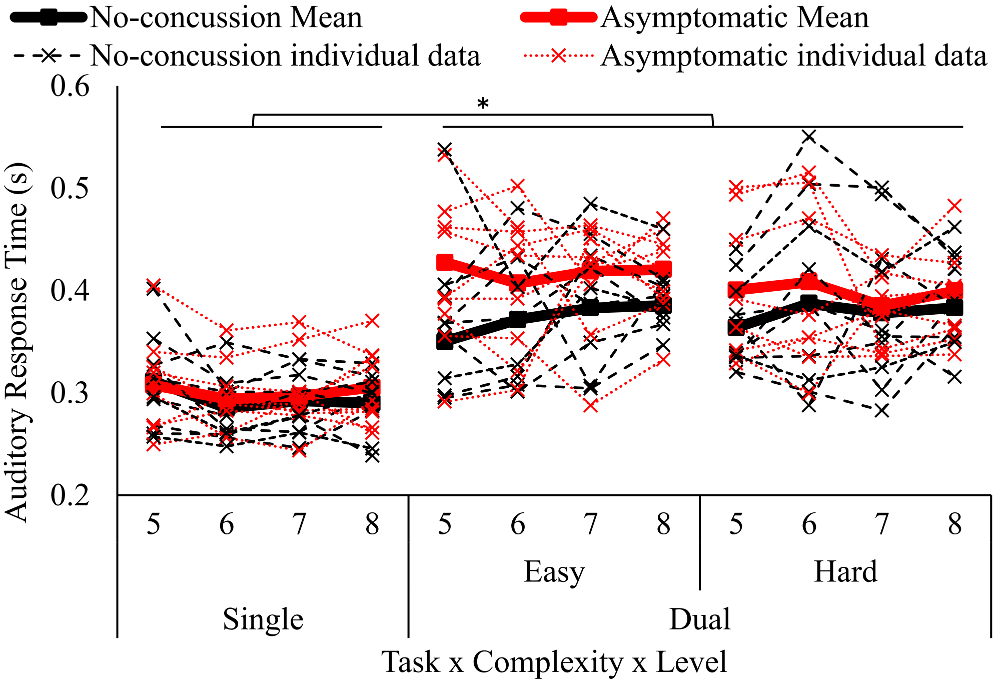
Note. The x-axis is separted by task condition and level. Errors were higher in the dual-task compared to single-task in both groups but those with a concussion history performed more errors in the dual-task compared to those without.

Auditory oddball response time (RT)

There were no significant main effects of concussion history, complexity, or set size and no interactions (see Figure 5.8).

Figure 5.8

Auditory response time (s)



Note. The x-axis is separated by task condition (single, dual), complexity (easy, hard), and level (5 to 8).

5.4 DISCUSSION

The goal of the current study was two-fold: 1) to examine what type of load (perceptual or cognitive) is imposed by Corsi pattern complexity, and 2) to assess the repeatability of previous findings which showed that individuals with a history of concussion perform worse in a dual-task condition compared to those without a concussion. Our manipulation of Corsi complexity (i.e., crosses, angles, distance) within a set size was successful because recall accuracy was lower for the hard patterns compared to the easy patterns at all set sizes. Notably, the hard patterns at lower set sizes (five and six blocks) were recalled with similar accuracy as the easy patterns at higher set sizes (seven and eight blocks). Contrary to our hypothesis, Corsi pattern complexity did not affect the auditory oddball task performance indicating that it is unlikely that Corsi pattern complexity influences perceptual load. The finding that pattern complexity affects the accuracy of Corsi task performance may indicate that this manipulation affects cognitive load. Consistent with our previous work, auditory oddball performance was worse in those with a concussion history in the dual-task (Studies one and two; Tapper et al., 2017) indicating that some of these participants appear to have difficulty performing two tasks simultaneously.

Our dual-task paradigm is not ideally suited to test Lavie's theory because the secondary task was not a "distractor" task. Nonetheless, this framework still provides a useful probe to assess the type of load imposed by path configuration complexity. Our findings do not support the idea that Corsi pattern complexity imposes a perceptual load. Instead, these findings are consistent with previous research by Bor et al., (2003) who suggested that pattern complexity reflects a cognitive load because symmetrical patterns can be selected into organizational chunks by relating familiar shapes to object-based information held in long-term memory. Interestingly, Bor et al (2003) found greater fMRI activation in the DLPFC (an area associated with attention and executive control), inferior parietal lobule, and fusiform gyrus during encoding of symmetrical compared to asymmetrical patterns suggesting that the chunking process might require executive control and consume attentional capacity. Further research by Bor and Seth (2012) indicated that attention and memory chunking appear to be dissociable processes that are both supported by an overlapping neural network. An alternative explanation for these results is that encoding patterns at set sizes of five or more blocks, regardless of its pattern configuration, exceeded working memory capacity; thus, fewer attentional resources were available for the auditory task. Future studies should assess the effects of path complexity on auditory task performance at a set size of four blocks because it is within most individuals working memory capacity. Lastly, it is likely that there is a combination of perceptual and cognitive load during memory encoding in our task because this phase involves both perceptually processing new items while updating and maintaining older items in working memory. Therefore, it is difficult to dissociate between perceptual and cognitive load in the encoding phase regardless of pattern complexity.

Our findings could be also interpreted using Baddeley's working memory model. A large body of research shows reduced performance on the Corsi task while simultaneously performing a suppression task that relies on the visuospatial sketchpad or the central executive but not the phonological loop (Kemps, 2001; Rossi-Arnaud et al., 2006, 2012; Smyth & Scholey, 1994; Vandierendonck et al., 2004). For example, Kemps et al showed a reduction in Corsi task accuracy as set size increased from three to eight blocks and this reduction was steeper on asymmetrical (i.e., hard) compared to symmetrical (i.e., easy) patterns at set sizes of five to eight blocks; however, when performed simultaneously with a visuospatial suppression task (i.e., matrix tapping task), recall accuracy was reduced to the same degree on both pattern complexities (symmetrical, asymmetrical). Similarly, research by Rossi-Arnuald et al., (2006, 2012) found the same degree of reduction in Corsi accuracy on symmetrical and asymmetrical patterns when concurrently performing a central executive suppression task (i.e., verbal trails task) whereas no differences were found for a phonological suppression task (i.e., continuous word repetition). Our findings are consistent with this body of research. Importantly, we instructed participants to primarily focus on the Corsi task in the dual-task condition which revealed deficits on the auditory task that were unaffected by the complexity of the Corsi pattern. In contrast, other studies (Kemps, 2001; Rossi-Arnaud et al., 2006, 2012) instructed participants to perform both tasks together without explicitly instructing which task to prioritize; thus, individuals might have engaged in a strategy where they focused on the suppression task resulting in deficits on the Corsi task. Our study provides clearer evidence to support that better recall accuracy of an easy compared to hard pattern is not dependent on executive processes but likely reflects an automatic process where patterns can be reconstructed from common representations held in long-term memory (Kemps et al., 2001; Rossi-Arnaud et al., 2006, 2012). Therefore, the capacity to encode hard compared to easy patterns is not a more attentionally demanding process because it had no further effects on auditory performance, but likely reflects a less efficient chunking process where harder pattern configurations do not benefit from common representations held in long-term memory (i.e., redundant shapes).

Research into the long-term effects of concussion has shown that individuals with a history of concussion perform similarly to a control group on tasks involving working memory (Bernstein, 2002; Ozen et al., 2013; Thériault et al., 2011) or auditory tone discrimination (i.e., auditory oddball task; Bernstein, 2002; De Beaumont et al., 2009; Gosselin et al., 2006; Witt, Lovejoy, Pearlson, & Stevens, 2010) when these tasks are performed alone. Our results are consistent with these studies showing no between groups differences on either task when it is performed alone. In contrast, compared to a control group, individuals with a history of concussion showed reduced performance on the auditory oddball task when performed concurrently with the eCorsi task. In context of Lavie's theory, this finding might indicate that tasks loading perceptual processing are helpful in discriminating between individuals with a history of concussion compared to those without. Only one study to our knowledge has examined perceptual load in individuals with a history of mild to moderate TBI, ranging from three months to 20 years post injury (Waters, 2010). They found that individuals with a history of TBI had more errors when detecting a peripheral distractor (i.e., ignored the distractor more often) under low and high perceptual loads compared to controls. Interestingly, these between group differences were evident on two separate perceptual load tasks including one designed to replicate Lavie's original experiment (Lavie, 1995) and the other designed to be more ecologically valid by using real-life pictures such as a cup. Thus, this might provide some indication that the availability of attentional capacity is reduced in individuals with a history of TBI, including concussion. However, one issue raised by Waters (2010) is that participants in the TBI group could have had difficulty remembering task instructions, which might have increased the cognitive load resulting in less efficient allocation of attention. This limitation along with the difficulty to clearly dissociate between perceptual and cognitive load in the encoding phase of our task prevents definitive conclusion about the type of load that is most sensitive in discriminating between groups.

This study does involve some limitations that should be addressed in future research. First, the number of auditory tones presented at each set size was relatively small (i.e., 10-13 target tones per pattern difficulty per set size). As a result, our estimate of auditory target accuracy and response time in the dual-task condition were based on a relatively small number of auditory tones. Because the in-person research was limited and our access to a student-athlete population was reduced due to the COVID pandemic, the task was kept short (approximately 30 minutes complete) in order to recruit as many student-athletes as possible. This allowed us to collect 19 varsity and competitive recreational team-sport athletes. Secondly, the sample size for a between groups comparison was somewhat small (9 controls, 10 asymptomatic); however, when collapsed into a single group, it did surpass the sample size calculation of twelve that was needed to investigate the effects of Corsi pattern complexity on auditory performance. Nevertheless, the between group (no concussion, asymptomatic) results replicated previous findings in our lab (Study 1 and 2; Tapper et al., 2017); thus, offering some confidence about the repeatability of between group differences. Lastly, our task was not ideally suited to study Lavie's theory, instead the framework was used to probe our understanding of the dual-task paradigm. Future research could test what type of load is most sensitive to concussion history using tasks developed to study the load theory (Forster & Lavie, 2009; Konstantinou et al., 2014; Konstantinou & Lavie, 2013; Lavie & Dalton, 2014).

5.5 CONCLUSION

The current study further characterized task-related properties that influence performance on the dual-task paradigm and replicated previous findings that individuals with a history of concussion show subtle long-term deficits when dual-tasking (Tapper et al., 2017). It is unlikely that path complexity influences perceptual load because performance on the secondary auditory oddball task was not affected by pattern configuration complexity. Thus, encoding easy patterns, compared to hard patterns, into working memory might represent an automatic process where common pattern shapes are integrated with pre-existing representations held in long-term memory resulting in improved recall accuracy. Importantly, dual-task paradigms appear to be sensitive in discriminating between individuals with and without a history of concussion. Further investigation into the type of load most sensitive to the long-term effects of concussion will help in the development of a task that can be used by clinicians to help manage concussions.

Section 6 – Summary of Research

6.1 GENERAL DICUSSION

Research over the past two decades has shown that dual-task assessments offer valuable insight about cognitive recovery following a concussion. In particular, dual-task paradigms have been shown to discriminate between individuals with and without a concussion in the acute (hours), sub-acute (days to months), intermediate (6-12 months) and chronic (>1 year) phase post-injury (see reviews by Kleiner et al., 2018; Register-Mihalik et al., 2013). In contrast, single-task assessments encompassed in many neuropsychological batteries only detect cognitive dysfunction in the acute and sub-acute phases (Schatz et al., 2006) but show no differences between groups in the intermediate and chronic phase (Broglio et al., 2009; Maerlender et al., 2010). These findings suggest that current neuropsychological tests are not sensitive enough in detecting long-term subtle cognitive dysfunction following a concussion. Despite numerous dual-task assessments showing sensitivity in the long-term, these assessments have yet to be implemented into clinical practice. Two main limitations have halted the use of dual-task assessments for clinical utility; first, most dual-task assessments involve balance or gait measures, which commonly require extensive set up and expensive tools to administer (e.g., motion caption monitors, force plates); however, newer research have shown less expensive tools (i.e., accelerometers) to be affective (Kleiner et al., 2018); and second, the psychometric properties of these tasks are not well established (e.g., repeatability, factors that influence performance measures) (Kleiner et al., 2018; Register-Mihalik et al., 2013). The novelty of the current thesis was to address some of these limitations using an easy-to-administer, computer based dual-task paradigm that has previously been shown to discriminate between individuals with and without a history of concussion (Tapper et al., 2017).

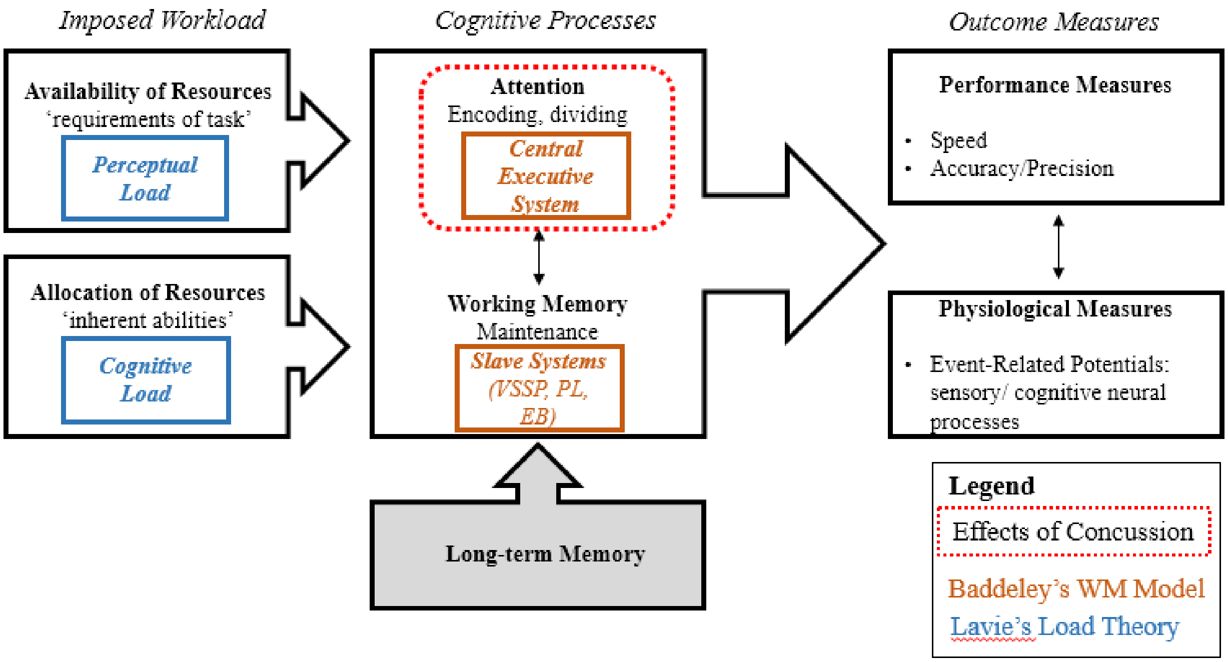
The first two studies in this thesis were designed to understand the underlying neural mechanism(s) contributing to the long-term cognitive dysfunction. Results revealed that sensory gating appears to be a ‘hard-wired’ mechanism that can be up-regulated or down-regulated based on the availability or direction of attention and might influence processes occurring at the later, cognitive stages of information processing in individuals without a history of concussion. In particular, a larger sensory gating amplitude at the N100 ERP was associated with a reduction in the amplitude of the P300 ERP thought to reflect cognitive stages of information processing (i.e., P300 ERP) when workload was high. This process might occur to protect higher order cortical areas from being bombarded with irrelevant information. Examination of sensory and cognitive ERPs in individuals with a history of concussion showed that they have difficulty gating relevant from irrelevant sensory information at early sensory processing stages (i.e, P50, N100), which might reduce the availability of attention or ability to allocate attention at the cognitive processing stages (i.e., P300). Specifically, previously concussed individuals appeared to have more difficulty facilitating relevant auditory stimuli, as reflected by smaller target N100 ERPs, and this was associated with a reduction in cognitive processing at the P300 ERP when mental workload was high. Interestingly, individuals with a history of concussion might try to compensate by activating a sensory gating network earlier in the processing stream as reflected by better P50 ERP gating in the dual-task condition compared to single-task condition.

The latter two studies of this thesis assessed the factors that influence performance measures and the utility of a portable tool. Results showed that using a phone device provides a valid assessment of working memory capacity; however, the characteristics of the eCorsi task must be taken into consideration as changing the pattern complexity within a set size significantly reduced recall accuracy. Lastly, changing the pattern characteristics of the eCorsi task does not appear to consume additional attentional capacity because secondary auditory task performance did not change as a function of pattern complexity, instead auditory performance was reduced to the same degree by both pattern complexities in the dual-task condition. This supports the idea that memory chunking is not an attentionally demanding process but benefits from pre-existing long-term memory representations resulting in better Corsi recall accuracy on easy compared to more difficult patterns. Overall, the body of work in this thesis provides valuable insight into task-related properties that influence dual-task performance which have implications for developing a task that is sensitive in detecting subtle long-term effects of concussion. Crucially, dual-task paradigms that stress attentional resources and are more ecologically valid (i.e., reflect tasks involved in everyday life), thus, may be helpful in assessing the long-term assessment of concussion.

This work was guided by a framework developed to test the long-term effects of concussion focusing on mental workload (see Figure 1.1). Mental workload was defined as the effort required by an individual to achieve a certain level of performance and emerged from the interaction between the availability of resources, requirements of the task and environmental context. The imposed workload influences cognitive processes that are needed to attend to a task and to encode, maintain and recall items stored in working memory. Importantly, two highly recognized theoretical frameworks, Lavie's load theory and Baddeley's working memory model, were influential in the development and interpretation of the findings from each study. As a result, the mental workload framework presented in the introduction was modified to encompass components of Lavie's load theory and Baddeley's WM model (see Figure 6.1) and to provide a stronger explanation of the findings. In Figure 6.1, the imposed workload emerges from the interaction between the availability of resources (i.e., requirements of the task) and the allocation of resources (i.e., individual's inherent abilities), which both influence the cognitive processes of attention and working memory. The ***imposed workload*** that influences the availability of resources is perceptual load because attentional capacity becomes bottlenecked as the perceptual processing demands increase. On the other hand, ***the imposed workload*** that influences the allocation of resources is cognitive load because it reflects an impaired prioritization process that competes for processing resources. The ***cognitive process*** of attention can be best described by the central executive component of Baddeley's WM model, which acts as a supervisory control system responsible for directing attention towards a task, monitoring and coordinating mental operations, and encoding items to be stored in one of the slave systems (i.e., phonological loop and visuospatial sketchpad). Whereas the ***cognitive process*** of working memory represents Baddeley's slave systems (i.e., visuospatial sketchpad, phonological loop), which are responsible for temporarily storing and rehearsing items, as well as remembering task instructions. Long-term memory mainly interacts with working memory (i.e, slave systems) by influencing the storage and rehearsal of a sequence. For instance, the storage of a sequence can be improved by pre-existing representations held in long-term memory, which facilitate memory chunking, whereas sequences without a representation suffer from the capacity limitations of working memory. The findings of this thesis would support the idea that individuals with a history of concussion have a deficit in the ***cognitive process*** of attention (i.e., Baddeley's central executive component) due to a reduction in perceptual processing capacity or a difficulty in efficiently allocating attentional resources. This would be reflected in the reduction in N100 and P300 target amplitudes and might indicate that these individuals have troubles selecting or facilitating relevant information in their environment, which becomes important when task demands increase and mental workload is stressed.

Figure 6.1

Modified framework of mental workload



Note. The imposed workload is influenced by the allocation of resources and availability of resources. In context of Load theory, perceptual load can be increased by increasing the perceptual processing demands of the task whereas cognitive load can manipulated by increasing the amount of information held in working memory. The cognitive process of attention appears to be most affected by a concussion, which is analogous to Baddeley's central executive component. In contrast, working memory capacity (or the slave systems) appear to be unaffected by a concussion, at least in asymptomatic individuals.

6.2 LIMITATIONS

There are some additional limitations in the methods and the analysis approach which need to be addressed. First, the correlation between behavioural and electrophysiological outcomes were not conducted because these measures are often not correlated. For instance, multiple studies have shown changes in electrophysiological measures without changes in behaviour outcomes, especially in those with a history of concussion (Bernstein, 2002; De Beaumont et al., 2009; Witt et al., 2010). This is likely because electrophysiological measures represent an ensemble of many cortical and sub-cortical processes that contribute to the stimulus-response relationship such as sensing a stimulus, understanding what it is, and deciding upon an appropriate response. Thus, a correlation between any ERP measure and behavioural outcome would be difficult to interpret because of the many complex neural processes that occur within the stimulus-response timeframe. Second, eCorsi pattern complexity within a set size were not controlled for in the first two studies; thus, the range of pattern complexity varied (see Appendix B, Figures 7.2 and 7.3). This is important because the workload for ERP measures in the dual-task condition were separated by set size (2-4, 5-6, 7-8 blocks); however, within set size workload might have contributed to changes in ERP measures. As highlighted in studies three and four, eCorsi difficulty is dependent on both set size and the complexity of a pattern such as its average angle, number of path crossings, and distance of path trajectory. Since the pattern complexity within a set size did not affect any secondary task measure, as shown in study four, it might indicate that this would also not affect any ERP measure because these ERPs are thought to reflect processes of attention (Broglio et al., 2009). Unfortunately, there were not enough ERPs within a set size to make the comparison between patterns with higher recall accuracy compared to lower recall accuracy. Thirdly, ERPs were measured using the baseline-to-peak method. One potential weakness of this method is that it does not account for shifts in amplitude resulting from a preceding potential. For instance, a larger P50 amplitude would shift the N100 amplitude to be more positive (i.e., smaller negativity) whereas a larger N100 amplitude would shift the P300 amplitude to be smaller. One advantage of the baseline-to-peak method is its ability to isolate potentials that might be contributing to an effect. In addition, the baseline-to-peak method has been used extensively in research examining mental workload (Kasper et al., 2014; Singhal et al., 2002; Solis-Marcos & Kircher, 2019; Ullsperger et al., 2001) and the long-term effects of concussion (Bernstein, 2002; Broglio et al., 2009; De Beaumont et al., 2009; Thériault et al., 2011), thus, it allowed for a better interpretation of the results because it can be compared to previous literature. Fourthly, symptomology was measured using 22 questions with a six-point Likert scale on how a person felt on the date of testing. This approach may not reflect individuals who experience symptoms related to their concussion on other dates or provide detail on other symptoms related to concussion such as sleeping habits. Because of the heterogeneity of concussion and range of symptoms that can manifest, a more detailed symptom questionnaire would be helpful in understand other characteristics that could be contributing to dual-task performance. Lastly, categorization of individuals with a concussion history was based on self-report of a previously diagnosed concussion by a medical professional. It is possible that some individuals in the no-concussion group may have experienced a concussive or sub-concussive event in their lifetime that was not diagnosed by a medical professional. We did try to control for this by asking participants if they had ever fallen or been hit and felt symptoms such as dizziness, confusion, headaches, or others. In addition, reporting depended on the individual's ability to accurately remember a concussive event, a process that can be affected by a brain injury. As concussion diagnosis criteria improves and more effective medical documentation is implemented, the process of appropriately categorizing individuals with a concussion history compared to those without will improve. Until then, the current approach allowed us to gain some insight into the potential long-term effects of concussion.

6.3 FUTURE DIRECTIONS

There are numerous avenues for future research to advance the work presented here. The first and most interesting is whether the attentional impairments in individuals with a history of concussion are due to a reduction in attentional capacity (i.e., perceptual load), a problem properly allocating attentional resources (i.e., cognitive load) or an overall impairment in attention that can be probed using both types of tasks. This is fundamentally important when assessing the acute to chronic effects of a concussion for the purpose of developing a task that can effectively track the recovery process following a concussion. Another direction for future research is to explore the association between performance on computer-based cognitive tasks and real-life performance. Research has shown that individuals who sustained one concussion are at a two-fold increased risk for sustaining a second concussion within a year (Nordstrom, Edin, Lindstromg, & Nordstrom, 2013; Nordstrom, Nordstrom, & Ekstrand, 2014). In addition, those with a concussion history are at a four-time greater risk for suffering all types of injuries (e.g., musculoskeletal) within 6-12 months post-concussion (Herman et al., 2009; Nordstrom et al., 2014). One theory is that the brain is more sensitive to re-injury because of increased lactate build-up, which leaves neurons more vulnerable for a subsequent concussion (Guskiewicz et al., 2003). Alternatively, these individuals might have difficulty perceptually processing information in their environment resulting in increased risk for subsequent injury because they are not able to efficiently process multisensory inputs in highly demanding and complex environments. Thus, tests that stress mental workload would be helpful in the management of concussion because they could identify individuals who might be more susceptible to subsequent injury and allow medical professionals to make more accurate decisions on a safe return to play. Lastly, this dual-task paradigm may be helpful to study mental workload outside the scope of brain injury because it stresses cognitive functions (i.e., attention, working memory) that are important for engaging in daily activities. For instance, this paradigm may be helpful in identifying individuals who are susceptible to late life cognitive impairment or to understand the process of aging and disease (i.e., Alzheimer’s disease, dementia).

6.4 CONCLUSION

In conclusion, the research in this thesis brings us closer to a neurocognitive tool that can be used by clinicians to identify individuals who suffer from persisting albeit subtle cognitive dysfunction following a concussion. The findings addressed important gaps in our understanding of the long-term effects of concussion (i.e., changes in sensory and cognitive information processing) and the influential task-related properties that can be changed in the current dual-task paradigm to evaluate these long-term effects. In addition, this research provides evidence that cognitive impairments following a concussion may last months to years following an injury, which raises the questions of whether current concussion management tools are sensitive enough in determining return-to-play decisions.

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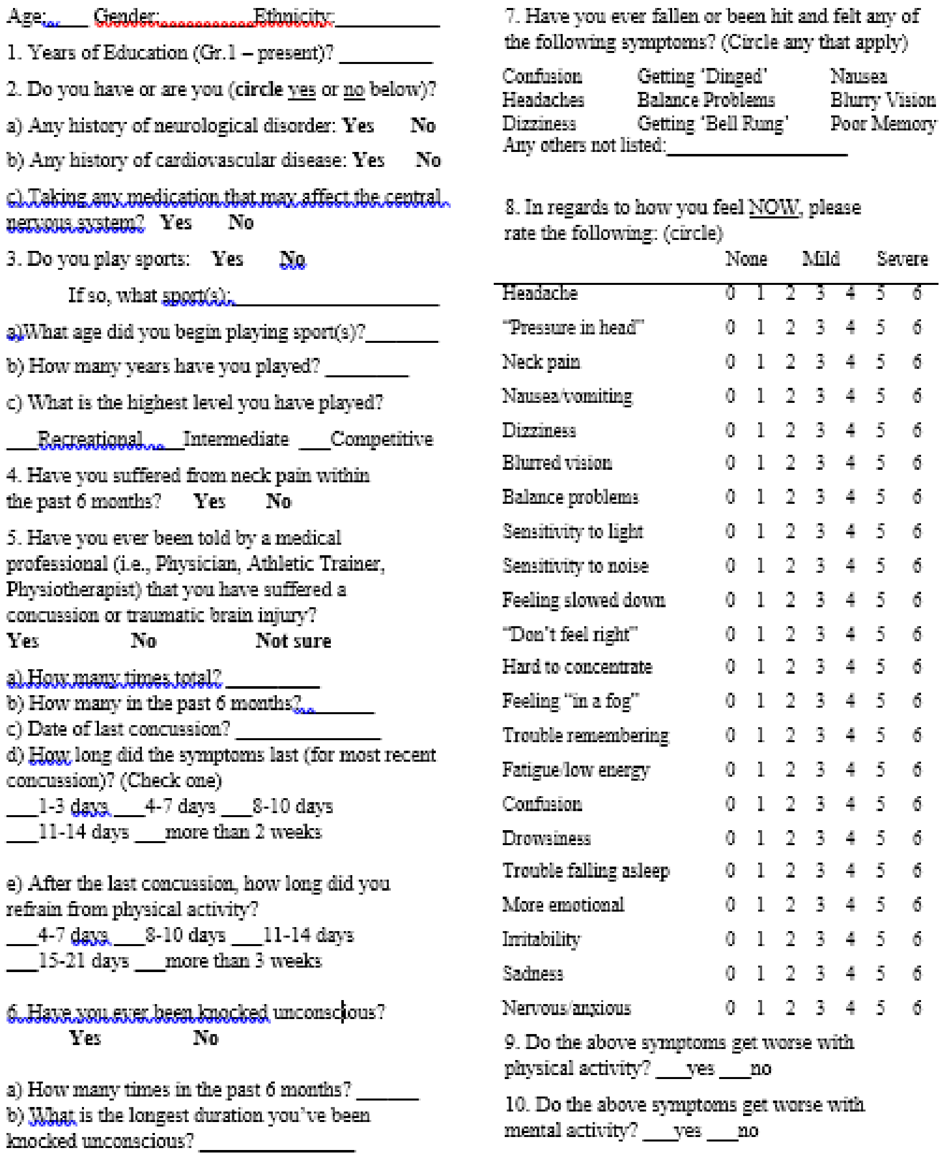
APPENDIX A – PRE-SCREENING ASSESSMENTS

Waterloo Health History Questionnaire



Age:____ Gender:__________ Ethnicity:__________

1. Years of Education (Gr.1 – present)? ________

2. Do you have or are you (**circle** yes or no below)?

a) Any history of neurological disorder: **Yes** **No**

b) Any history of cardiovascular disease: **Yes** **No**

c) Taking any medication that may affect the central nervous system? **Yes** **No**

3. Do you play sports: **Yes** **No**

If so, what sport(s):________________

a)What age did you begin playing sport(s)?______

b) How many years have you played? _______

c) What is the highest level you have played?

___Recreational ___Intermediate ___Competitive

4. Have you suffered from neck pain within the past 6 months? **Yes** **No**

5. Have you ever been told by a medical professional (i.e., Physician, Athletic Trainer, Physiotherapist) that you have suffered a concussion or traumatic brain injury?
Yes **No** **Not sure**

a) How many times total? ________
b) How many in the past 6 months?______
c) Date of last concussion? ___________
d) How long did the symptoms last (for most recent concussion)? (Check one)
___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

6. Have you ever been knocked unconscious?
Yes **No**

a) How many times in the past 6 months? _____
b) What is the longest duration you've been knocked unconscious? _____________

7. Have you ever fallen or been hit and felt any of the following symptoms? (Circle any that apply)

Confusion
Headaches
Dizziness
Getting 'Dinged'
Balance Problems
Getting 'Bell Rung'
Nausea
Blurry Vision
Poor Memory
Any others not listed:______________

8. In regards to how you feel NOW, please rate the following: (circle)

	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

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

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

APPENDIX B – Supplementary Methods and Findings

Study 1 Corsi block test

Table 7.1

Path configuration characteristics

# of blocks	Sequence	# of crossings	Average angle
5	8,7,4,3,6	1	81
	3,5,1,7,2	1	50
	5,3,4,6,1	0	62
	2,6,3,4,8	2	30
6	1,7,2,8,5,4	3	45
	7,3,6,1,4,8	2	53
	5,8,6,4,2,1	0	100
	3,5,8,7,6,4	0	82
7	4,2,6,8,3,7,5	0	77
	8,2,5,3,4,1,6	2	48
	2,6,4,8,3,5,1	2	59
	3,5,8,7,4,1,6	0	94
8	1,5,8,7,2,6,3,4	5	65
	2,4,6,8,1,3,5,7	2	92
	1,6,7,4,2,8,5,3	0	70
	7,5,6,3,8,7,4,2	2	67

Figure 7.1

Corsi target recall accuracy as a function of the number of path crossings and set size.

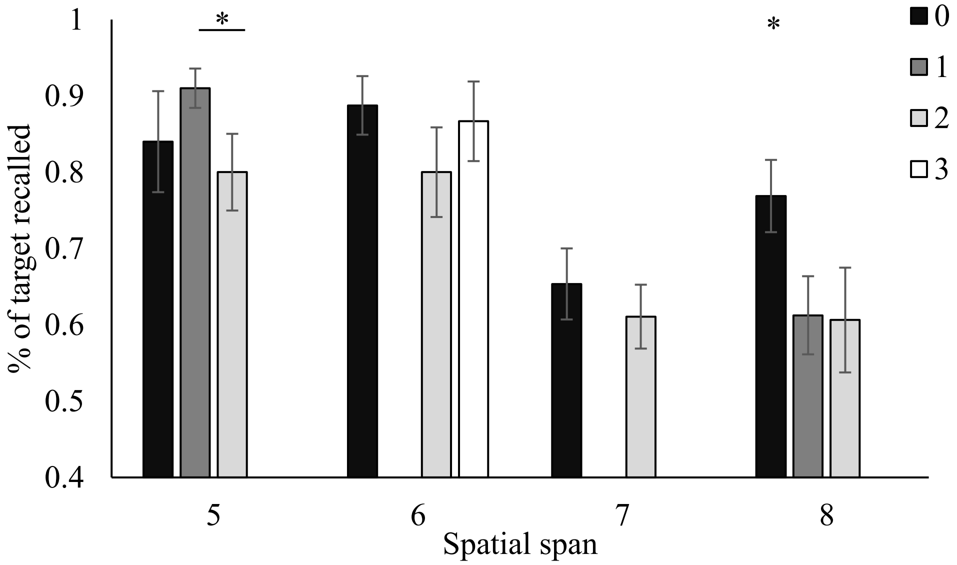
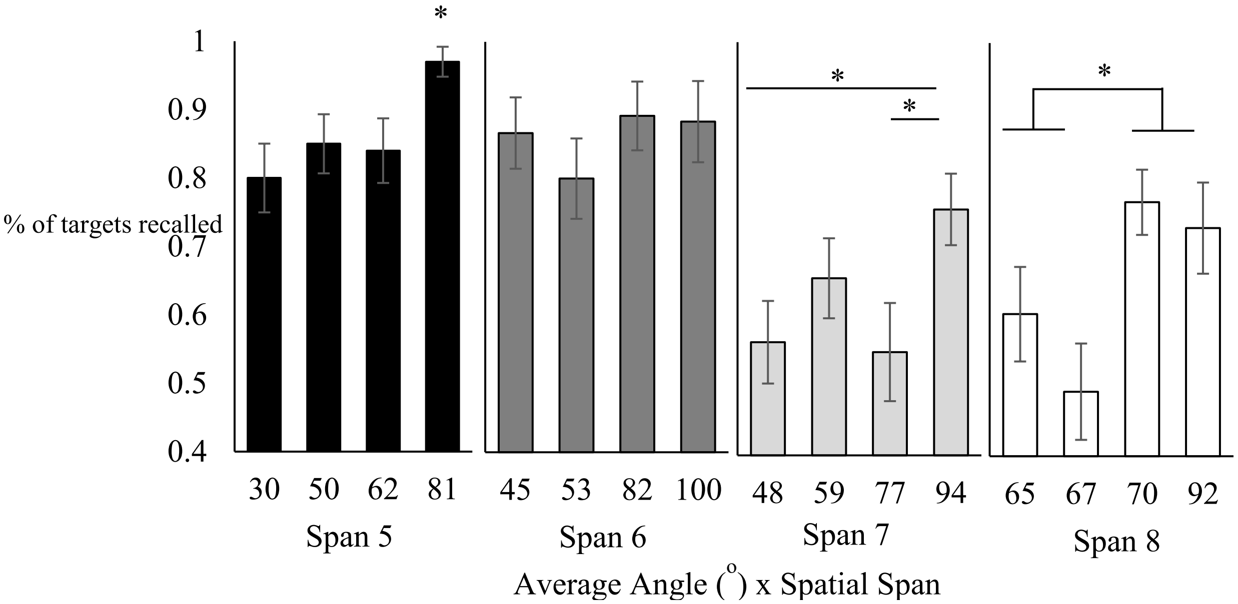


Figure 7.2

Corsi target recall accuracy as a function of average sequence angle separated by set size.



Study 3 Sequence characteristics

Table 7.2

Average angle, number of crossings and path length for Corsi sequences.

Set size	Workload	Average Angle in ° (rank)	# of Crossings (rank)	Computer path length (mm)	Phone path length (mm)	Cuml rank score (sum)	Rank
5	Easy	91 (1)	0 (1)	676 (2)	178	4	1
		86 (2)	0 (1)	460 (1)	121	4	2
		84 (3)	1 (3)	725 (3)	191	6	3
	Hard	40 (4)	2 (4)	1086 (6)	286	14	5
		35 (5)	2 (4)	843 (4)	222	13	4
		22 (6)	3 (6)	988 (5)	260	17	6
6	Easy	94 (1)	1 (1)	942 (2)	248	4	1
		72 (2)	2 (3)	915 (1)	241	6	2
	Medium	65 (3)	1 (1)	1060 (4)	279	8	3
		52 (4)	2 (3)	1035 (3)	273	10	4
	Hard	43 (5)	3 (5)	1303 (5)	343	15	5
		37 (6)	4 (6)	1615 (6)	425	18	6
7	Easy	85 (1)	4 (4)	1402 (6)	369	11	4
		80 (2)	3 (2)	1303 (2)	343	6	2
	Medium	62 (3)	1 (1)	1132 (1)	298	5	1
		57 (4)	3 (2)	1352 (4)	356	10	3
	Hard	32 (5)	7 (6)	1398 (5)	368	16	6
		29 (6)	4 (4)	1303 (2)	343	12	5
8	Easy	94 (1)	1 (1)	1132 (1)	298	3	1
		73 (2)	4 (3)	1352 (2)	356	7	2
	Medium	58 (3)	3 (2)	1447 (4)	381	9	3
		45 (4)	10 (5)	1664 (6)	438	15	5
	Hard	37 (5)	5 (4)	1398 (3)	368	12	4
		35 (6)	10 (5)	1615 (5)	425	16	6

APPENDIX C

Summary of studies using the visual-auditory dual-task paradigm to compare individuals with and without a history of concussion.

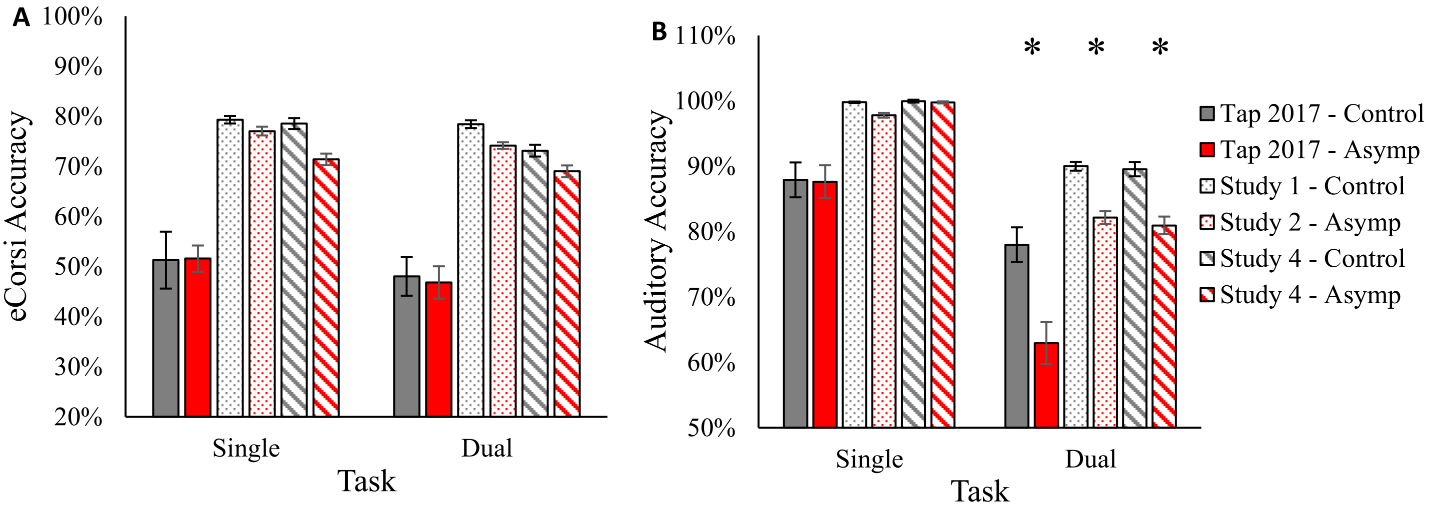
Table 7.3: Summary of dual-task paradigms

STUDY	METHODS	SUMMARY
TAPPER ET AL., (2017)	Participants (11 No-concussion; 18 Asymptomatic) 1. Corsi block task • 2 tr/set size, set size 2 to 8 blocks • discontinue when both wrong @ same set size • No control for path config. • Trial accuracy (% of trials correctly recalled) 2. Auditory Choice RT task • Double-click high tone/single-click low tone • Auditory accuracy (%) 3. Dual-task • Corsi (primary) + Auditory	Corsi accuracy no difference between groups or task condition Auditory accuracy was reduced in dual-task compared to single, and in asymptomatic group in the dual-task compared to controls
STUDY 1 & 2	Participants (20 No-concussion [18 for ERPs]; 16 Asymptomatic [12 for ERPs]) 1. Corsi block task • 4 tr/set size, set size 2 to 8 • Performed all trials • No control for path config. • Target accuracy (% of trgts recalled) 2. Auditory Oddball task • Single-click high tone (target: 25%)/ignore low tone (non-target: 75%) • ERPs time locked to tones • Target accuracy (% of trgt tones responded too correctly), Errors of commission (% responses to non-trgt tones), & Response time (ms) 3. Dual-task • Corsi (primary) + Auditory	Corsi maintained in both groups between task conditions Both groups auditory acc, errors of comm., & RTs worse in dual-task; but, asymptomatic was lower in all auditory measures. Controls had better N100 sensory gating as workload increased compared to Asymp P300 ERP decreased as a function of load (set size & task) & concussion history (control > asymp)
STUDY 4	Participants (9 No-concussion; 10 Asymptomatic) 1. Corsi block task	Corsi accuracy decreased as a function of set size & path

	- 6 tr/set size, set size 5 to 8 - Performed all trials - Path config controlled for (Easy: no crossings, avg. angle > 70°, shorter distances; Hard: >2 crossings, avg. angle < 45°, longer distances) - Target accuracy (% of trgts recalled) 2. Auditory Oddball task - Single-click high tone (target: 40%)/ignore low tone (non-target: 60%) - Target accuracy (% of trgt tones responded too correctly), Errors of commission (% responses to non-trgt tones), & Response time (ms) 3. Dual-task - Corsi (primary) + Auditory	configuration difficulty in both groups Corsi pattern difficulty did not effect auditory performance measures but increases in set sizes reduced performance Asymptomatic performed worse on auditory accuracy in dual-task compared to controls. No differences in single-task performance on either task

Figure 7.3

eCorsi (A) and auditory (B) accuracy separated by task condition and study



Note. Full gray (control) and red bars (asymptomatic) are from the published study by Tapper et al., 2017. The dotted gray (no-concussion) and red bars (asymptomatic) are from studies one and two in this thesis whereas the horizontal line gray (no-concussion) and red (asymptomatic) bars are from study four in this thesis. The paradigms from each study were slightly different but involved a primary eCorsi task and a secondary auditory tone discrimation task.