EXAMINING THE COGNITIVE EFFECTS OF SUBCONCUSSIVE IMPACTS

IS IT WORTH THE HIT? EXAMINING THE COGNITIVE EFFECTS OF SUBCONCUSSIVE IMPACTS IN SPORT USING EVENT-RELATED POTENTIALS

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Lay Abstract

A concussion is a devastating injury that can greatly affect how an individual functions in their day-to-day life. Concussions are often discussed in the context of contact sports because of these athletes' exposure to repeated head impacts. That said, another cause for concern is the effects of head impacts that do not result in a concussion per se – these are known as subconcussive impacts. A brain imaging technique known as electroencephalography (EEG) involves recording brain activity from sensors on the head. Conducting this recording while individuals perform tasks known to evaluate brain function offers an opportunity to assess symptoms rather than relying on a patient's own, subjective report of their experiences. The present study investigated the use of EEG in evaluating the effects of subconcussive impacts in collegiate athletes and found that repeated head impacts can reduce cognitive health, even if they do not result in a diagnosis of concussion.

Abstract

Concussion is a life-altering injury that can affect people of all ages. Event-related potentials (ERPs) extracted from electroencephalography (EEG) have proven sensitive to concussion-induced cognitive deficits. The MMN, P3a, P3b, and N2b are some ERP components of interest, assessing automatic attention, attentional resource allocation, working memory, and inhibitory executive function, respectively. These ERPs can assess some common symptoms associated with concussion at a level that cannot be attained using self-report. A reduced amplitude and potentially delayed latency of the P3a and P3b is a well-replicated result in concussion research. Furthermore, recent research suggests that an alteration in amplitude of earlier peaks such as the N2b and MMN might represent an irreversible change in cognitive processing that tends to occur in the chronic stages of concussion. Many of these studies have focused on athletes, however little research has evaluated the cognitive effects of sustaining numerous blows to the head that do not result in a clinical diagnosis of concussion, as is the case for many athletes in contact sports. These blows are often referred to as subconcussive impacts. The present study examined the cognitive and neurophysiological effects of subconcussive impacts on collegiate contact-sport athletes and compared them to non-contact athletes. The athletes completed questionnaires to evaluate their health and athletic history, as well as estimates of exposure to subconcussive impacts such as position and playing time, prior to participating in three paradigms meant to assess various cognitive processes during an EEG recording. Across two experiments we

demonstrated that subconcussive impacts within a season of play can result in alterations in neurophysiological markers of cognitive health. Our findings also reveal that continued involvement in contact sports can have serious implications in one's automatic attention, resource allocation, and working memory as demonstrated by reduced ERP amplitudes in contact as compared to non-contact athletes.

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List of All Abbreviations and Symbols

Ag/AgCl: Silver/silver chloride

ANOVA: Analysis of variance

BDI-II: Beck Depression Inventory II

BVA: BrainVision Analyzer

CTE: Chronic Traumatic Encephalopathy

dB: Decibels

DB: Defensive Back

df: Degrees of Freedom

DL: Defensive Lineman

DRL: Driven-right leg

DT: Duration Tone

EEG: Electroencephalography

EOG: Electrooculogram

ERP: Event-related potential

FB: Fullback

FT: Frequency Tone

HIT: Head Impact Telemetry (System)

Hz: Hertz

ICA: Independent components analysis

ImPACT: Immediate Post-Concussion Assessment and Cognitive Testing

IT: Intensity Tone

LB: Linebacker

MMN: Mismatch negativity

ms: Milliseconds

mV: Millivolts

OL: Offensive Lineman

PCSS: Post-Concussion Symptom Scale

PSS: Perceived Stress Scale

QB: Quarterback

RB: Running Back

ROI: Region of interest

S: Standard deviation

SAC: Standardized Assessment of Concussion

SF-36: Short-Form Health Survey 36

SPL: Sound Pressure Level

ST: Special Teams

ST: Standard Tone

US: United States

WR: Wide Receiver

μV: Microvolts

1. Introduction

1.1. Prevalence and Significance of Concussion in Sport

A traumatic brain injury, regardless of its severity, can greatly alter an individual's lifestyle both acutely and chronically. An estimated 1.6–3.8 million sports-related traumatic brain injuries occur each year in the United States alone (Langlois et al., 2006). One such brain injury is a mild traumatic brain injury (mTBI), or as it is more commonly known, a concussion. In Ontario alone nearly 1.2% of the population (or about 150, 000 individuals) sustain a concussion each year (Langer et al., 2020). Considering the widespread impact of this injury, there has been increasing interest in developing a better understanding of its etiology as well as its persistent effects as seen in over 40% of individuals more than one year after sustaining a concussion (Rutherford, 1989). This interest has affected the world of contact sports in particular. Unfortunately, many concussions are left undiagnosed and, therefore, untreated. There is a dire need to create an objective assessment tool for concussion, which would improve diagnosis, prognosis, symptom severity, and the tracking of recovery.

The incidence of concussion in sport as well as the question of when an athlete is fit to return to play following such an injury are just some of the factors that have led to a growing interest in sports-related concussion, specifically. In the most recent consensus statement on concussion in sport, concussion was defined as a traumatic brain injury induced by biomechanical forces to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head

(McCrory et al., 2017). This definition emphasizes the fact that contrary to common belief, being hit directly in the head is not a requirement for the acquisition and diagnosis of a concussion. Repeated concussions have cumulative effects on an individual's health, especially when one does not fully recover from one concussion prior to sustaining a second, related injury (Bey & Ostick, 2009). As such, there is a dire need for a tool, or set of tools, that can accurately assess concussion and subsequent recovery.

1.2. Concerns About Long-lasting Symptoms of Concussion and Repeated Head Impacts

Recent research has found that the effects of concussion can often persist well beyond the presentation of symptoms. There is reason to believe that cognitive and other health deficits found in elderly individuals who sustained a concussion up to decades earlier could be attributed, at least in part, to their earlier injury. These deficits have been investigated both through neuropsychological testing and through neurophysiological testing. Neuropsychological results are mixed, but do tend to demonstrate patterns of increased sadness, depressive symptoms, and/or mild cognitive impairment in athletes with a history of concussion and related impacts (Omalu et al., 2005; Guskiewicz et al., 2005; Guskiewicz et al., 2007). Ruiter et al. (2019) studied a population of retired Canadian Football League (rCFL) players who on average sustained their last concussion 28 years prior to testing. Compared to healthy controls, they found that the rCFL group had decreased general health and increased overall depressive symptoms. Furthermore, it was found that the rCFL groups showed delays in neurophysiological responses linked to attentional processing stimuli as well as a reduced cognitive capacity to allocate attentional resources. De Beaumont et al. (2009) found similar neurophysiological results, in addition to reduced episodic memory and response inhibition, in a sample of retired football players and hockey players who had sustained their last concussion over 30 years prior to participation in this study.

In addition to neuropsychological and neurophysiological concerns that have been raised, there is also a large body of research suggesting that repeated head trauma can have neurodegenerative effects that manifest as a disease known as Chronic Traumatic Encephalopathy (CTE) (Omalu et al., 2005; McKee et al., 2009; Baugh et al., 2012; Hazrati et al., 2013; Mez et al., 2017). CTE is a progressive neurodegenerative condition that at present can only be detected post-mortem through autopsy reports, and is of particular concern to athletes with a history of involvement in high contact sports (Baugh et al., 2012).

1.3. What are Subconcussive Impacts?

In high-contact, collision-prone sports athletes tend to sustain numerous cranial impacts that do not lead to a concussion diagnosis on clinical grounds; this is commonly referred to as a subconcussive impact (Bailes et al., 2013). Preliminary research using the Head Impact Telemetry (HIT) System has helped us to understand key characteristics such as the quantity and magnitude of these head impacts, suggesting that the average high school football player experiences 652 impacts per season (Broglio et al., 2011), while the average collegiate football player experiences 1000 impacts per season (Gysland et al., 2012). Moreover, several studies have found that the incidence of subconcussive impacts in football varies according to player position such that linemen and linebackers tend to sustain the greatest number of head impacts, but the lowest magnitude of impacts (Crisco et al., 2010; Crisco et al; 2011). Whereas running backs and quarter backs sustain the greatest magnitude head impacts (Crisco et al., 2011). Due to the startling quantity of hits sustained in one season alone, researchers have begun to examine whether subconcussive impacts, like concussions themselves, can have acute and/or long-term cognitive effects. When researchers followed 46 collegiate football players over the course of one season they found that there was no significant change in neurological function as examined by five clinical measures (Gysland et al., 2012). However, it is well-documented that, largely due to practice effects, ceiling effects, and poor test-retest reliability, neuropsychological assessments tend to be insensitive to lasting concussion-induced deficits (Randolph et al., 2005). Thus research has shifted to focus on neurophysiological assessments. It has now been shown that there is a dose-response relationship between neurological impairment and the number of head impacts sustained in a population in football players, but more importantly it was found that numerous football players that had been repeatedly hit in the head without being diagnosed with a concussion showed neurophysiological changes (Breedlove et al., 2012).

1.4. Introduction to Electroencephalography and Event-related Potentials

There is currently a need for a more objective tool in the clinical diagnosis and assessment of concussion. Numerous brain imaging techniques have been proposed as a solution to this issue, however the ease-of-use and affordability of electroencephalography (EEG) have made it a particularly attractive option as a potential clinical tool. EEG is a form of brain imaging that involves recording cortical brain activity from an array of electrodes strategically placed on an individual's scalp. Due to the method of recording, EEG has poor spatial resolution as compared to other methods of brain imaging such as MEG or fMRI. However, its temporal resolution is excellent, resolving down to milliseconds (Chiappa, 1990; Duncan et al., 2009). The temporal resolution of EEG allows for the extraction of event-related potentials (ERPs) – waveforms with particular characteristics of latency, topography, and amplitude that are time-locked to an event or experimental manipulation. An understanding of these ERPs, often referred to as ERP components, can reveal important information about cognitive function (Duncan et al., 2009).

1.5. ERPs as Indicators of Cognitive Function

Over the last several decades a large body of research has involved the role of ERP components as indicators of various cognitive functions. Some examples of such components are the N170, N400, Phonological Mismatch Negativity (PMN), P600, N200 (including the N2a or Mismatch Negativity [MMN], N2b, N2pc, and N2c subcomponents), and P300 (including the P3a and P3b subcomponents). The N170 is an early component associated specifically with the processing of faces as demonstrated by the face inversion effect (Bentin et al., 1996; Rossion et al., 1999). The PMN, previously thought to be an N200 variant, is elicited in response to the occurrence of an unexpected phonological sound typically in the terminal word of a sentence (Connolly et al., 1990; Connolly et al., 1992; Connolly & Phillips, 1994). As such, the PMN is thought to reflect phonological processing. The N400 and P600 are also involved in language processing. However, unlike the PMN, the N400 is primarily elicited due to semantic incongruencies or constraints (Duncan et al., 2009), whereas the P600 is elicited by a syntactic anomaly (Osterhout & Holcomb, 1992). The N200 can be divided into several sub-components including the N2a (commonly referred to as the mismatch negativity or MMN) which is elicited to pre-attentive stimulus processing, the N2b which is thought to reflect higher-order executive functions requiring conscious attention, the N2c which is sensitive to stimulus classification, and the N2pc which is implicated in visual search (Luck & Hillyard, 1994; Patel & Azzam, 2005; Folstein & Van Petten, 2008; Bolduc-Teasdale et al., 2012). Finally, the P300 consists of two commonly known subcomponents: the P3a and P3b, which are associated with stimulus discrimination and working memory, respectively (Comerchero & Polich, 1999; Goldstein et al., 2002; Polich, 2007). Due to the nature of this thesis, we will focus on two components that are associated with cognitive functions compromised by concussion, namely the P300 (both the P3a and P3b subcomponents) and the N200 (specifically the MMN and N2b).

1.5.1. P300

The P300 is one of the most commonly studied ERP components in concussion and subconcussive research. It is characterized by a large, broad, positive peak that typically occurs around 300 ms after the onset of a rare, task-relevant stimulus (Duncan et al., 2009). The P300 is elicited traditionally by an oddball paradigm – a paradigm in which participants are presented with a disproportionately large number of regular (standard) stimuli relative to the number of deviant stimuli (e.g. 82% standard and 18% deviant) and are required to respond differentially depending on the type of stimuli they encountered. In other words, the oddball task requires individuals to attend to and make judgements on the stimuli presented to them. Thus, the P300 is considered to be sensitive to levels of attentional processing as well as the allocation of attentional resources (Johnson et al., 2004; Polich, 2007). However, the oddball is not the only design that is able to elicit a P300. In a series of vocabulary tests Connolly et al. (1999) found that the P300 was elicited when participants correctly identified the definition of a word within the scope of their vocabulary, but not when they knew a definition to be incorrect or when a word was beyond their vocabulary level. It was, therefore, concluded that the P300 in this context reflected primarily information transmission.

More recent research has distinguished between an early and late component of the P300, the P3a and P3b, respectively. It is believed that the two components further distinguish between levels of attention (Polich, 2007). The P3a is distributed in a fronto-central manner (Comerchero & Polich, 1999; Goldstein et al., 2002; Polich, 2007), and is often elicited in response to rarely occurring, task-relevant stimuli such as a loud tone in a series of quieter tones or a high-pitched tone in a series of lower-pitched tones (Squires et al., 1975; Goldstein et al., 2002; Polich, 2007). As such, the P3a is said to be implicated in task processing and stimulus discrimination (Comerchero & Polich, 1999; Goldstein et al., 2002; Polich, 2007). The P3b is involved in context updating operations and memory storage (Polich, 2007), and typically has a parietal distribution (Comerchero & Polich, 1999; Goldstein et al., 2002; Polich, 2007).

Recent unpublished work in the Language, Memory, and Brain Lab at McMaster University revealed that the P300 can also be generated by the Continuous Visual Memory Test (CVMT). The CVMT was found to be a valid tool to assess visual memory without relying heavily on verbal or motor responses (Trahan & Larrabee, 1988; Larrabee & Trahan, 1992). The task involved presenting participants with complex, ambiguous drawings in succession, and asking whether the stimuli were "old" or "new" in the context of this experiment. Several years later, Harker and Connolly (2007) adapted this task to evaluate whether ERPs could be used to discriminate memory performance. What they found was that not only did their computer-adapted version of the CVMT correlate well with alternate, previously-validated forms of the CVMT, but also that the ERPs were able to reveal interesting information about the cognitive processes at play. Specifically, visual inspection revealed the presence of both an early and late positive component (i.e. the P3a and P3b) for both old and new stimuli, as well as differential P300 amplitudes across stimulus type. One of the purposes of the present study is to demonstrate the use of CVMT in detecting concussion-induced cognitive deficits and explore its sensitivity to subconcussive impacts. Research has shown that the CVMT is able to distinguish participants with moderate to severe traumatic brain injury from healthy controls, however no published work has demonstrated such effects in individuals with mild traumatic brain injury or a history of subconcussive impacts.

1.5.2. N200

The mismatch negativity (MMN) is the first subcomponent of the N200. Distributed in a fronto-temporal or fronto-central manner across the scalp (Näätänen et al., 1978; Garrido et al., 2009), the MMN is the negative component of a difference wave between responses to standard and deviant auditory stimuli (Näätänen et al., 1978; Näätänen et al., 2007; Garrido et al., 2009) occurring 100–250 ms following the onset of a deviant stimulus (Garrido et al., 2009). The latency of the peak varies depending on whether the tone deviates in frequency, duration, or intensity (Näätänen et al., 2004). It is typically evoked by the presentation of an oddball or deviant stimulus in a sequence of familiar stimuli, much like the P300. However, the MMN is elicited when an individual is not attending to the stimuli and is, in fact, attending to an entirely different stimulus or other type of distraction (Näätänen et al., 1978; Näätänen et al., 1993; Garrido et al., 2007). Thus, it is often said to reflect early, automatic attentional processing.

The N2b is a component of the N200 peak that immediately precedes the P3a. It is a negative peak with a fronto-central distribution that is thought to reflect inhibitory executive control processes (Heil et al., 2000). It tends to occur about 200 ms following the onset of a deviant, task-relevant stimulus. Previous research on changes to the N2b in a concussed population compared to healthy controls when using the standard P300 paradigm has been conflicting. Some research has demonstrated reduced N2b amplitude in concussed groups (Broglio et al., 2009; Ruiter et al., 2019), whereas other studies have found no change in N2b amplitude (Bernstein, 2002). It is worth noting that the studies that found significant reductions in N2b amplitude involved athletes who had suffered multiple concussions, whereas in studies showing no effects the participants' concussion histories were unclear. This could suggest that number of concussions is associated with N2b amplitude and thus that a reduction in N2b amplitude is indicative of a more permanent cognitive change.

The most robust task for eliciting the N2b is the go/no-go Flanker task, as it directly assesses inhibitory executive function. In the Flanker task (Eriksen & Eriksen, 1974; Folstein & Van Petten, 2008), participants are presented with a string of stimuli (e.g. SSSSS or SSHSS) but are told to focus only on a target stimulus, which always appears in the same location. Subjects are typically required to respond with either a left-click or right-click depending on the stimulus presented. Varying conditions are produced by altering the compatibility or congruency of the "flanking" (i.e. surrounding) stimuli with respect to the target stimulus. In ERP studies it has been found that incompatible or incongruent conditions elicit slower responses and a larger N2b (Folstein & Van Petten, 2008). Due to constraints surrounding the number of protocols that could be included in the present study, the Flanker was not included to investigate the N2b. Rather, the auditory oddball task described above was used to elicit the N2b along with the P3a and P3b.

1.6. Subconcussive Impacts and ERPs

Few studies to date have examined the utility of ERPs in evaluating the effects of subconcussive impacts. Knowing that certain ERPs such as the P300 and N200 have demonstrated sensitivity to cognitive deficits due to concussion, we propose their use in assessing cognitive deficits due to repeated subconcussive impacts. A study comparing contact athletes with a history of concussion (concussion group), contact athletes with no history of concussion (subconcussive group), and non-contact athletes at a single time point found attenuated P3a and P3b amplitudes in the concussion and subconcussive group compared to the non-contact group (Moore et al., 2017). Note that although athletes in the subconcussive and control groups were presumed not to have sustained a diagnosed concussion, the researchers asked athletes in both groups if they had ever experienced a blow to the head, neck, or body that led to them experiencing concussion-like symptoms in case they had sustained an undocumented concussion; if yes, they were excluded from the analyses. Another study involving collegiate football players compared upper years to first years as well as a control group (Wilson et al., 2015). Using an auditory P3b oddball task paired with a simple visual distractor, researchers found no change in P3b amplitude over the course of one season, but they did find that the upper years had a smaller P3b than the first years, suggesting an effect of cumulative exposure to head and body impacts. It is worth noting that there were variations in timing from pre- to post-season (range: 171-217 days), potentially offering an explanation for the lack of pre-to post season effects especially given the small sample size of seven participants per group.

Furthermore some of the participants included in the study had a history of concussion, however a univariate analysis revealed that concussion history did not affect the results, thus offering support for their conclusion that these effects were due to subconcussive impacts. Finally, a more extensive study examining alterations in P3b amplitude across a season of collegiate football also considered how player position and frequency of impacts might contribute to these findings (Brooks, 2016). It was found that P3b amplitude was attenuated during and immediately following a season of play, and that these effects could recover at a follow-up test. Players were tested on average 10.58 days following their final impact for post-season testing, and then again on average 116.89 days after their final impact for follow-up testing, offering strong evidence of the utility of the P3b in assessing the progression of neurophysiological responses following a season of subconcussive impacts. Furthermore, these effects varied across player position and number of head impacts. Together these preliminary findings suggest that ERPs, specifically the P3a and P3b, can demonstrate sensitivity to subconcussive impacts as demonstrated by alterations in amplitude. In the present study we examine how numerous, subconcussive blows over the course of one season of play in a contact sport can affect various cognitive functions as demonstrated by several ERP components across three paradigms, and we begin to examine the contribution of additional factors to these effects.

1.7. This Study

The purpose of the present study is to understand how the cognitive processes of varsity athletes involved in contact sports are affected over the course of one season, and generally throughout their involvement in contact sports. The first experiment served as a pilot, allowing us to assess the utility of these paradigms in assessing subconcussive impacts, and prompting us to consider additional variables and/or manipulations that might help to answer our research questions. In the first experiment, we recruited athletes from various sports and conducting EEG testing pre-season, post-season, and after any concussions sustained throughout the season. Due to attrition, we were not able to conduct repeat testing on each athlete. As such, each group was considered independent. All athletes completed three tasks, each of which evaluated either attention or memory, during an EEG recording. We expected that athletes who sustained a concussion would show reduced cognitive function as demonstrated by reduced amplitudes and delayed latencies of the ERPs of interest. We also predicted that all athletes, regardless of their concussion history, would show similar deficits post-season but perhaps to a lesser extent in the absence of a concussion. Results revealed no group differences in the ERPs of interest pre-season as compared to post-season, however this is likely due to the small sample size as well as the lack of specificity in the athletes we recruited. No group analyses were performed post-concussion as there was only one participant in that category. However, two subjects were tested at more than one time point, allowing us to conduct single-subject analyses. Individual within-subjects analyses revealed differences in ERP amplitudes across time points. These results support the utility of EEG in the assessment of concussion, as well as provide evidence that subconcussive impacts can have negative consequences on cognitive health as detected by ERPs.

The issues mentioned in Experiment 1 were addressed in a follow-up experiment. The primary sample of interest was varsity football players, a group of athletes prone to consistent and severe impact during play, while the control sample consisted of athletes involved in non-contact sports such as swimming, rock climbing, or cross-country. All athletes completed the same tasks as in Experiment 1 and the contact (experimental) group was tested both pre- and post-season. The non-contact (control) group was tested once during their season. Group analyses revealed significant attenuation of several ERPs of interest in the contact group as compared to the non-contact group. We also found altered ERP latencies from pre- to post-season in the football players none of whom sustained a concussion during the season, suggesting a role of cumulative subconcussive impacts in altering some cognitive functions.

2. Experiment 1

2.1 Rationale and Objectives

2.1.1. Purpose

The purpose of this experiment was to investigate changes in ERP characteristics due to concussion and subconcussive impacts in athletes involved in contact sports across a season of play, and to explore the utility of three independent paradigms in doing so. This experiment served as a pilot, examining the utility of these paradigms in answering our primary research questions. This study also introduced the use of a visual memory task as well as an automatic attention task in investigating ERP changes following subconcussive impacts.

2.1.2. Research Question and Hypotheses

The research question investigated in this study was: are there changes in neurophysiological markers of cognitive function across a season of play in contact sports? We hypothesized that P3a and P3b ERP amplitudes would be attenuated post-season as compared to pre-season, and that this same attenuation would be seen in the concussed group but perhaps to a greater extent. The effects of all other ERP components were considered exploratory.

2.1.3. Objectives

The primary objectives of this study were as follows:

1. To investigate differences in P200, MMN, N2b, P3a, and P3b characteristics in athletes in contact sports across a season of play;
2. To replicate findings indicating that P3a and/or P3b amplitude is attenuated following repeated head impacts both in the presence and absence of a clinically diagnosed concussion;
3. To broaden our understanding of the MMN and head trauma;
4. And to investigate ERPs associated with visual memory directly through the CVMT.

2.2. Methods

2.2.1. Participants

Subjects were recruited through personal contacts in the Department of Athletics and Recreation, and postings around the McMaster University campus. This study was approved by the Hamilton Integrated Research Ethics Board (HIREB).

A total of 11 participants from McMaster University varsity sports teams were recruited (5 as preseason baseline subjects, 1 seventeen days post-concussion, and 5 in the post-season; mean age: 20.4, range: 18-23; 6 male, 5 female). All participants were athletes from either the varsity basketball, rugby, or football team. Participants were all fluent English speakers, had normal or corrected-to-normal vision, had no history of hearing or speech/language problems, and were not taking any medications that act on the central nervous system. All participants provided informed consent prior to participating in the experiment.

2.2.2. Procedure

There were three time points for testing: pre-season, following a concussion, and post-season. Due to attrition not all participants were tested at two different time points as initially intended, resulting in a between-subjects design.

Participants completed all self-report batteries mentioned above as well as the Edinburgh Handedness Inventory (Oldfield, 1971) – as some research has demonstrated task-dependent hemispheric asymmetries based on handedness (Galin et al., 1982) – and a pre-screening form prior to EEG testing. The pre-screen included reports of participants' age, sex, current medications, vision, hearing, and other background information that might serve as a confound in our study. A computerized survey was also administered to evaluate concussion history in all participants.

During testing participants sat in a chair directly facing a computer monitor. Participants were administered three different tasks, and the participants were provided with a set of instructions prior to each task (see below). The entire experiment was approximately one hour in duration.

2.2.3. Behavioural Tasks

Participants were administered several subjective behavioral assessments prior to the EEG experiment, including the Beck Depression Inventory II (BDI-II), Short Form Health Survey (SF-36) version 2 (v2), Edinburgh Handedness Inventory, and the Post Concussion Symptom Scale (PCSS) (see Appendices for questionnaires). The BDI-II, SF-36, and PCSS self-report tests were used to evaluate the overall health and well-being of participants. The BDI-II, specifically, was a means of assessing individual levels of depression (Beck et al., 1996), while the SF-36 was an indicator of general health by evaluating measures such as vitality, physical functioning, emotionality, mental state, and general health perceptions (McHorney et al., 1993). Lastly, the PCSS assessed symptom severity following a concussion as well as concussion-like symptoms in healthy individuals (Chen et al., 2007).

2.2.4. EEG Stimuli and Experimental Conditions

Each participant was tested in three paradigms used to examine distinct cognitive processes that are reflected in event-related potentials (ERP). Paradigms were presented in a predetermined order represented by the order in which they are discussed. The first task, P300 Oddball, required participants to fixate on the white cross located in the centre of a black screen while listening to tones through noise-cancelling earphones. This began with a practice run prior to advancing to the testing phase to ensure that the participants understood the instructions

This auditory P300 oddball task (adapted from Todd et al., 2008) consisted of one standard tone (ST; 1000 Hz, 80 dB Sound Pressure Level (SPL), 50 ms duration), as well as three types of deviant tones: 1) frequency (FT; 1200 Hz, 80 dB SPL, 50 ms), 2) intensity (IT; 1000 Hz, 90 dB SPL, 50 ms), and 3) duration (DT; 1000 Hz, 80 dB SPL, 100 ms). Each stimulus had an onset and offset ramp of 15 ms. The inter-stimulus interval (ISI) was 1000 ms. The ST was presented 492 times (82% of the stimulus set), while each deviant tone was presented 36 times, each accounting for 6% of the stimulus set.

Prior to testing, participants were instructed to right-click a mouse in response to all deviant tones, and left-click in response to each ST. These instructions were reversed halfway through the paradigm in order to counterbalance the auditory correlates of the mouse click. It was expected that this task would elicit an N2b, P3a, and P3b.

In the next paradigm participants completed the Continuous Visual Memory Test (CVMT) in which they were presented with a series of complex visual images and required to judge each one as to whether they had seen it before in the experiment. Participants were instructed to right-click or left-click the mouse depending on whether they thought the image was "old" or "new." The response correlates of the mouse click were counterbalanced across participants, as was the order of presentation of the images. This paradigm was expected to elicit a P3a and P3b.

The third protocol was the similar to the oddball task (adapted from Todd et al., 2008) In this final task, participants were instructed to watch a film, but not to attend to the tones that were being presented through the earphones. The film was muted so that participants were only hearing the tones. The two differences from the original oddball task were: the duration of the ISI and the absence of a response requirement. This version of the oddball task was designed to examine the MMN, a marker of predictive coding (Garrido et al., 2007; Garrido et al., 2009) or automatic attentional capture (Näätänen et al., 2007). Each deviant tone was presented 144 times (each type of deviant tone represented 6% of the stimulus set), whereas the ST was presented 1968 times, thereby representing 82% of the stimulus set. Therefore, a total of 2400 tones were used (with a 627-673.4 ms ISI; this varied consistently within and across participants). Participants were instructed to attend to a visual stimulus (a silent nature film) and to ignore the tones.

2.2.5. EEG Recordings

Electroencephalography (EEG) was recorded from 64 Ag/AgCl electrodes (International 10-20 system) using a BioSemi ActiveTwo system. Raw EEG was digitally sampled at 512 Hz and filtered online with a 0.01–100 Hz bandpass filter and a 60 Hz notch filter. Five Ag/AgCl external electrodes were placed on the subject's nose, left and right mastoids, and above and beside the outer canthus of the left eye. The electrooculogram (EOG) was recorded from the external electrodes placed above and over the outer canthus of the left eye and was digitally sampled and filtered identically to the EEG. Electroencephalography acquisition was referenced online to the driven right leg (DRL) and common mode sense (CMS), then re-referenced offline to the average of the mastoids. The CMS-DRL active reference voltage offsets were measured during setup. The acceptable threshold was between +20 and -20 mV.

2.2.6. Behavioral Data Analysis

Group differences were assessed using descriptive statistics and t-tests.

Statistical analysis of the PCSS, SF-36, and BDI-II were conducted in R Studio 1.2.5033 using Welch's two-sample t-test assuming unequal variances, and Welch's corrected degrees of freedom were reported. Statistical significance was considered at $p<0.05$.

2.2.7. EEG Data Analysis

Electroencephalography data were digitally filtered offline using the Butterworth Zero Phase Filter in Brain Vision Analyzer (v2.01), with a bandpass filter of 0.1-30 Hz (24 dB/oct). Data were visually inspected such that artifacts (e.g. due to movement) were manually removed. Automatic rejection of artifacts occurred for data with a voltage step greater than 50 µV/ms, data with a difference of values of greater than 200 µV in a 200 ms interval, and data with activity lower than 0.5 µV in a 100 ms interval. Additionally, Ocular Independent Component Analysis (ICA), with a maximum voltage criterion of +/-100 µV, was performed to remove vertical and horizontal eye-movement artifacts (Vigário, 1997). Data were then segmented into -200 ms pre- to 1000 ms post-stimulus intervals, and then averaged per condition. Only correct response trials were used for the P300 and CVMT protocols. Difference waveforms, where applicable, were produced by subtracting ERPs recorded to the standard stimulus (ST) from those recorded to each of the deviant tones (i.e., intensity (IT), frequency (FT), and duration (DT)). Finally, a process of automated peak detection (Barr et al., 1978) was performed on the difference waveforms and/or the averaged waveforms to obtain the maximal electrophysiological response of each ERP within their respective time windows. Within the P300 protocol, peak analyses were conducted on mean amplitude for the N2b (175–275 ms), P3a (275–375 ms), and P3b (400–700 ms) ERP components for each condition. Peak analyses on mean amplitude within the CVMT protocol were conducted on the P3a (275–375 ms) and P3b (400–700 ms). Finally, peak analyses on mean amplitude within the MMN protocol were conducted for the MMN (150–250 ms) and P200 (250-350 ms). All peak analyses were performed on the signed amplitude.

The 64 electrode scalp positions on the head were divided into 20 segregated Regions of Interest (ROIs) (Frishkoff et al., 2011). Each region consisted of three to six electrodes based on clustering from left (L), midline (M), and right (R) positions with frontal (F), central (C), and parietal (P) positions. After extracting the average ERPs, nine of these ROIs were grouped into three independent scalp sections: frontal (R-F, M-F, L-F). central (R-C, M-C, L-C), and parietal (R-P, C-P, L-P).

Statistical analyses were performed for both amplitude and peak latency using mixed-effects analysis of variance (ANOVA) with the between factor of group at two levels (pre-season and post-season), and the within factor of condition at three levels (frequency, duration, and intensity), and of ROI at 9 levels (see above). Analysis of latency did not include the within factor condition of ROI. The results of the Shapiro-Wilks test for normality suggest that the data may not be normally-distributed, however we ran an ANOVA as there is no non-parametric equivalent of the mixed-effects ANOVA, and parametric tests have been shown to provide lower rates of false positives (Thatcher et al., 2005) and better discriminate differences between groups (Sakkalis et al., 2008). Degrees of freedom were corrected using the more conservative Greenhouse-Geisser estimates of epsilon (Greenhouse & Geisser, 1959; Collier et al., 1967) to minimize the probability of Type 1 errors. EEG analyses were conducted on the peak amplitude and latencies of the difference waves for each condition in the P300 and MMN (intensity, frequency, and duration), and on the peak amplitude and latencies of the averaged waveforms for each condition of the CVMT (non-repeated and repeated). To achieve good statistical power (0.8) for all analyses would have required 18 participants in each group. We recognize that due to the small sample size in this study our statistical power may not be high. Thus, we take caution in interpreting our results and focus primarily on trends.

2.3. Results

2.3.1. Behavioural

All participants completed the BDI-II, SF-36 Short Form Survey, and PCSS after providing written informed consent. One participant did not complete the entire BDI-II questionnaire, therefore their BDI-II scores were discarded. All remaining participants completed all questionnaires (n=10).

The mean score on the BDI-II for the pre-season group was 4 (s=2.83), whereas the mean BDI-II score for the post-season group was 3.25 (s=2.5). There were no significant differences in depression scores between the pre-season and post-season groups.

The SF-36 organizes results into eight categories: physical functioning, role physical, bodily pain, general health, vitality, social functioning, role emotional, and mental health. The post-season group reported a significantly higher score for bodily pain than the pre-season group ($t(1,8)=-2.46$, $p<0.05$) suggesting that the post-season group experienced less bodily pain than the pre-season group. However, there were no group differences in any of the other categories.

Finally, the mean PCSS score at pre-season was 16.2 (s=17.0), while at post-season the mean PCSS score was 7.4 (s=6.43). There were no significant differences in PCSS scores between the pre-season and post-season groups. See Table 1 for a summary of the behavioural results.

2.3.2. Neurophysiological Results

We examined group level differences in ERP characteristics for the following ERP components: P200, MMN, N2b, P3a, and P3b within the MMN Oddball Paradigm (Figure 1, Figure 2), P300 Oddball Paradigm (Figure 3), and CVMT Paradigm (Figure 4). In the intensity condition (IT) of the MMN Oddball Paradigm only we also examined differences in the P3a because visual inspection suggested a reduced amplitude in the post-season group as compared to the pre-season group

(Figure 1C, Figure 2C). Between-subjects analyses revealed no differences in ERP characteristics (amplitude or latency) between groups (Table 2). We did, however, note a trend through visual inspection of the CVMT averaged waveforms such that the post-season group appeared to have an attenuated P3a and P3b as compared to the pre-season group. The impact of this finding will be covered further in the discussion.

2.3.3. Case Studies

Two participants were tested at two different time-points allowing us to conduct within-subject analyses on individual subjects. AW was tested following a concussion and subsequently after a recovery period post-season. BM was tested at pre-season and post-season. The following section will provide a detailed summary of the results for each of these special cases.

Case 1: AW

AW was a member of the varsity men's Football team at McMaster University. He was tested 17 days post-concussion, and then again post-season. Between the first and second time point of testing AW sustained another concussion. The second testing session was 40 days after his most recent concussion. The two sessions were two months apart. Data analysis was performed using Brainstorm (Tadel et al., 2011), which is documented and freely available for download online under the GNU general public license (http://neuroimage.usc.edu/brainstorm). We ran Bonferroni corrected two-sample t-tests assuming unequal variance to compare the ERP waveforms at time point one to the ERP waveforms at time point two at electrodes Fz, Cz, and

Pz (significance level: $p<0.05$). Specifically, we compared the amplitude of the ERP components of interest within each condition of all three paradigms to examine whether any significant changes occurred over the elapsed time period.

The MMN oddball paradigm was examined across a time window of -100 ms to 301 ms. There were no significant findings within this window.

The CVMT paradigm was examined across a time window of -100 ms to 600 ms. There were no significant findings within this time window.

The P300 oddball paradigm was examined across a time window of -100 ms to 600 ms. There was a significant increase in ERP amplitude for the intensity condition of the auditory oddball task from 252-273ms at Fz, 271-296ms at Cz, and 306-312ms at Pz (Figure 5A). All other comparisons for this paradigm were not significant. These results suggest an increase in P3a amplitude, specifically to the intensity deviant from post-concussion to post-season.

Case 2: BM

BM was a member of the varsity men's Rugby team at McMaster University. He was tested at pre-season, and then again post-season. His testing sessions were nearly four months apart. Data analysis was conducted as with AW.

The MMN oddball paradigm was examined across a time window of -100 ms to 301 ms. There was a significant decrease in ERP amplitude for the intensity condition of the auditory oddball task from 207-258 ms at Fz and from 222-260 ms at Pz (Figure 5B). All other comparisons for this paradigm were not significant. These results suggest a reduction in P200 amplitude, specifically to the intensity deviant from pre-season to post-season.

Due to technical issues there were no CVMT data for BM.

The P300 oddball paradigm was examined across a time window of -100 ms to 600 ms. There was a significant increase in ERP amplitude for the intensity condition of the auditory oddball task from 187-223 ms at Fz and from 199-229 ms at Pz (Figure 5C). These results suggest an increase in N2b amplitude, specifically to the intensity deviant from pre-season to post-season.

2.4. Discussion

In this study we recruited athletes from McMaster University sports teams and tested them pre-season, following a concussion, and post-season in a between-subjects design. Participants completed behavioural questionnaires to evaluate their overall health as well as any concussion-related symptoms, then underwent an EEG recording while completing various computer tasks: the P300 Oddball Paradigm, the CVMT Paradigm, and the MMN Oddball Paradigm. The post-season group reported less bodily pain on the SF-36 than the pre-season group. Otherwise, we found no significant differences in behavioural scores between groups, suggesting that there were no underlying differences in depression scores, concussion-related symptoms, or overall health as assessed by the BDI-II, PCSS, and SF-36, respectively. We also found no significant differences between groups in latency or amplitude for any of our ERPs of interest, despite the trend of a reduced P3a and P3b amplitude in the post-season group as compared to the pre-season group in the CVMT. The trend in the CVMT offers some support for the utility of this paradigm in eliciting our ERPs of interest and assessing neurophysiological differences resulting from subconcussive impacts. At face value these findings might indicate that subconcussive impacts over the course of one season of contact sport do not significantly affect cognitive function as detected by ERPs. However, it is possible that this lack of an effect is due to the variability in our sample. To assess this possibility, we took advantage of two participants in the data set who were tested at two time points: AW and BM. We conducted individual subject comparisons within time windows that reflect our ERPs of interest to evaluate whether individual subjects experienced changes in ERP characteristics over these time frames.

AW was a varsity football player who was first tested 17 days post-concussion, and then again post-season, which happened to follow another concussion that had been sustained 40 days prior. Results indicate an increase in P3a amplitude in the intensity condition of the P300 Oddball Paradigm over what could be considered a recovery period following a concussion, which would suggest that his task processing and stimulus discrimination improved over time. In fact, it is worth noting that AW barely elicited a P3a in this task at all post-concussion in part because he performed poorly on the oddball task (likely due to concussion symptoms), hence the jitter seen in Figure 5A. This finding indicates that the P3a is sensitive to concussion-related symptoms and, more importantly, that it can track progress over time. However, this should be interpreted with caution given his poor performance at time point 1.

BM was a varsity rugby player who was tested at pre-season, and then again post-season. The results indicate a decrease in P200 amplitude in the intensity condition of the MMN Oddball Paradigm from pre-season to post-season and an elevated N2b amplitude to the intensity deviant in the P300 Oddball Paradigm. A reduced P200 amplitude suggests that a season of subconcussive impacts sustained during a season of rugby may disrupt early sensory processes, while an increased N2b amplitude may indicate the recruitment of compensatory neural resources to meet cognitive demands (Ledwidge & Molfese, 2016).

The findings from BM's case offer preliminary support for the hypothesis that subconcussive impacts due to involvement in contact sports can result in changes in neurophysiological markers of cognitive function , while the findings from AW's case offer support for previous findings that concussion-induced cognitive changes can be detected by ERPs. However, the presence of significant effects as seen in individual analyses despite the lack of a significant effect in group comparisons suggests at least one of three things: 1) these effects might be minor, 2) this sample was too small and too variable to demonstrate any underlying effects, 3) there are other factors to consider in understanding these effects. One factor to consider is the variability in the frequency and extent of the impacts acquired during a season of play. In a sport where different positions experience different levels of contact, such as football, the magnitude of subconcussive impacts is not consistent throughout the team. Previous research using the Head Impact Telemetry (HIT) System has found that in collegiate football players, linemen and linebackers tend to sustain the lowest magnitude of head impacts, but the largest number of impacts per game (Crisco et al., 2010; Crisco et al., 2011; Funk et al., 2012). Another factor that could affect the likelihood of finding a difference in ERP characteristics from pre- to post-season is concussion history. A study by De Beaumont et al. (2007) on university football players found that athletes with a history of multiple concussions showed a supressed P3 amplitude compared to those with no concussion history or those who had sustained a single concussion. These findings illustrate the importance of obtaining an extensive athletic and medical history in order to better understand the effects of concussions and subconcussive impacts on cognitive function.

Some limitations of this experiment include that the pre- and post-season time points were not well-controlled, therefore athletes were tested at various time points pre- and post-season. This study also contained a small sample, which may have compromised statistical power. Furthermore, we did not account for participants' concussion history or their involvement in their sport that season, both of which could contribute to their likelihood of sustaining an injury during the season and/or being subjected to subconcussive impacts. Finally, we did not include a true control group. Future work should consider not only how athletes differ across two time points, but also how they differ from a comparable group that perhaps is not subjected to the same types and/or frequency of impacts as these athletes.

Table 1: *Between-group differences in the behavioural scores on the BDI-II, PCSS, and SF-36 (v2).*

Behavioural Scores					
Assessment	Pre-season Mean (SD)	Post-season Mean (SD)	*df*	*t*	*p*
Beck's Depression Inventory II (BDI-II)	4 (2.83)	3.25 (2.5)	6.88	0.42	> 0.05
Post Concussion Symptom Scale (PCSS)	16.2 (17.02)	7.4 (6.43)	5.12	1.08	> 0.05
Short Form Survey (SF-36) v2					
Category					
Physical functioning	92.00 (9.09)	100 (0)	4	-1.97	> 0.05
Role lim. due to physical health	72.5 (31.12)	98.75 (2.79)	4.06	-1.88	> 0.05
Role lim. due to emotional problems	90 (10.86)	88.33 (13.94)	7.55	0.21	> 0.05
Vitality	58.75 (9.48)	71.25 (19.56)	5.78	-1.28	> 0.05
Mental health	76 (4.18)	83 (5.70)	7.34	-2.21	> 0.05
Social functioning	92.5 (11.18)	97.5 (5.59)	5.88	-0.89	> 0.05
*Bodily pain**	62 (15.21)	86 (15.62)	8.00	-2.46	< 0.05*
General health	75.6 (9.74)	83.6 (12.36)	7.58	-1.14	> 0.05

Table 2: *Between-group differences in P3a, P3b, and N2b amplitude and latency within the P300 protocol, P3a and P3b amplitude and latency within the CVMT protocol, and MMN, P200, and P3a (intensity condition only) amplitude and latency within the MMN protocol.*

P300 Protocol				**CVMT Protocol**				**MMN Protocol**			
P3a Amplitude				***P3a Amplitude***				***MMN Amplitude***			
Effect	*df*	*F*	*p*	*Effect*	*df*	*F*	*p*	*Effect*	*df*	*F*	*p*
Group	8	0.00	> 0.05	Group	7	1.42	> 0.05	Group	8	0.02	> 0.05
Group:Condition	16	0.31	> 0.05	Group:Condition	7	0.79	> 0.05	Group:Condition	16	0.33	> 0.05
Group:Region	64	0.89	> 0.05	Group:Region	56	2.27	> 0.05	Group:Region	64	0.29	> 0.05
P3a Latency				***P3a Latency***				***MMN Latency***			
Effect	*df*	*F*	*p*	*Effect*	*df*	*F*	*p*	*Effect*	*df*	*F*	*p*
Group	8	0.12	> 0.05	Group	7	0.05	> 0.05	Group	8	0.19	> 0.05
Group:Condition	16	0.26	> 0.05	Group:Condition	7	0.77	> 0.05	Group:Condition	16	0.18	> 0.05
P3b Amplitude				***P3b Amplitude***				***P200 Amplitude***			
Effect	*df*	*F*	*p*	*Effect*	*df*	*F*	*p*	*Effect*	*df*	*F*	*p*
Group	8	0.26	> 0.05	Group	7	1.32	> 0.05	Group	8	0.01	> 0.05
Group:Condition	16	1.02	> 0.05	Group:Condition	7	0.49	> 0.05	Group:Condition	16	0.32	> 0.05
Group:Region	64	1.04	> 0.05	Group:Region	56	1.56	> 0.05	Group:Region	64	0.63	> 0.05
P3b Latency				***P3b Latency***				***P200 Latency***			
Effect	*df*	*F*	*p*	*Effect*	*df*	*F*	*p*	*Effect*	*df*	*F*	*p*
Group	8	0.51	> 0.05	Group	7	0.46	> 0.05	Group	8	0.19	> 0.05
Group:Condition	16	1.17	> 0.05	Group:Condition	7	0.00	> 0.05	Group:Condition	16	0.18	> 0.05
N2b Amplitude								***P3a Amplitude (Intensity condition only)***			
Effect	*df*	*F*	*p*					*Effect*	*df*	*F*	*p*
Group	8	0.24	> 0.05					Group	8	1.51	> 0.05
Group:Condition	16	0.33	> 0.05					Group:Region	64	1.55	> 0.05
Group:Region	64	0.99	> 0.05					***P3a Latency (Intensity condition only)***			
N2b Latency								*Effect*	*df*	*F*	*p*
Effect	*df*	*F*	*p*					Group	8	0.64	> 0.05
Group	8	3.19	> 0.05								
Group:Condition	16	1.30	> 0.05								

Note: ":" denotes an interaction

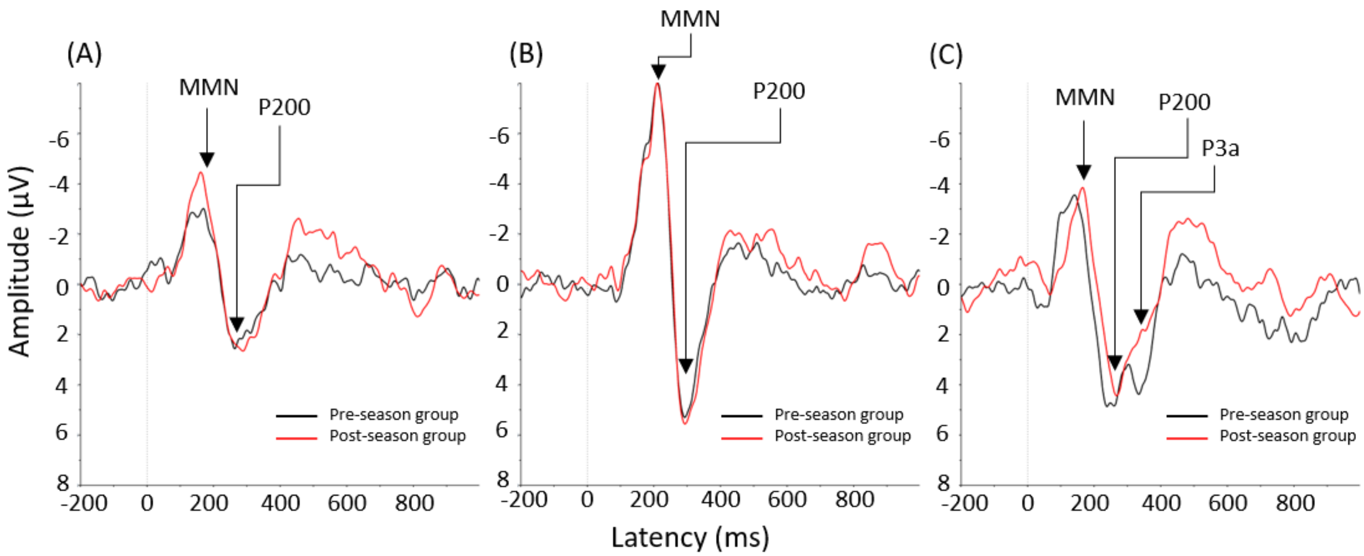

Figure 1: *Grand-averaged MMN protocol difference waveforms recorded at Cz for each group. Pre-season group: black; Post-season group: red. (A): MMN and P200 components evoked in the Frequency condition. (B): MMN and P200 components evoked in the Duration condition. (C): MMN, P200, and P3a components evoked in the Intensity condition.*

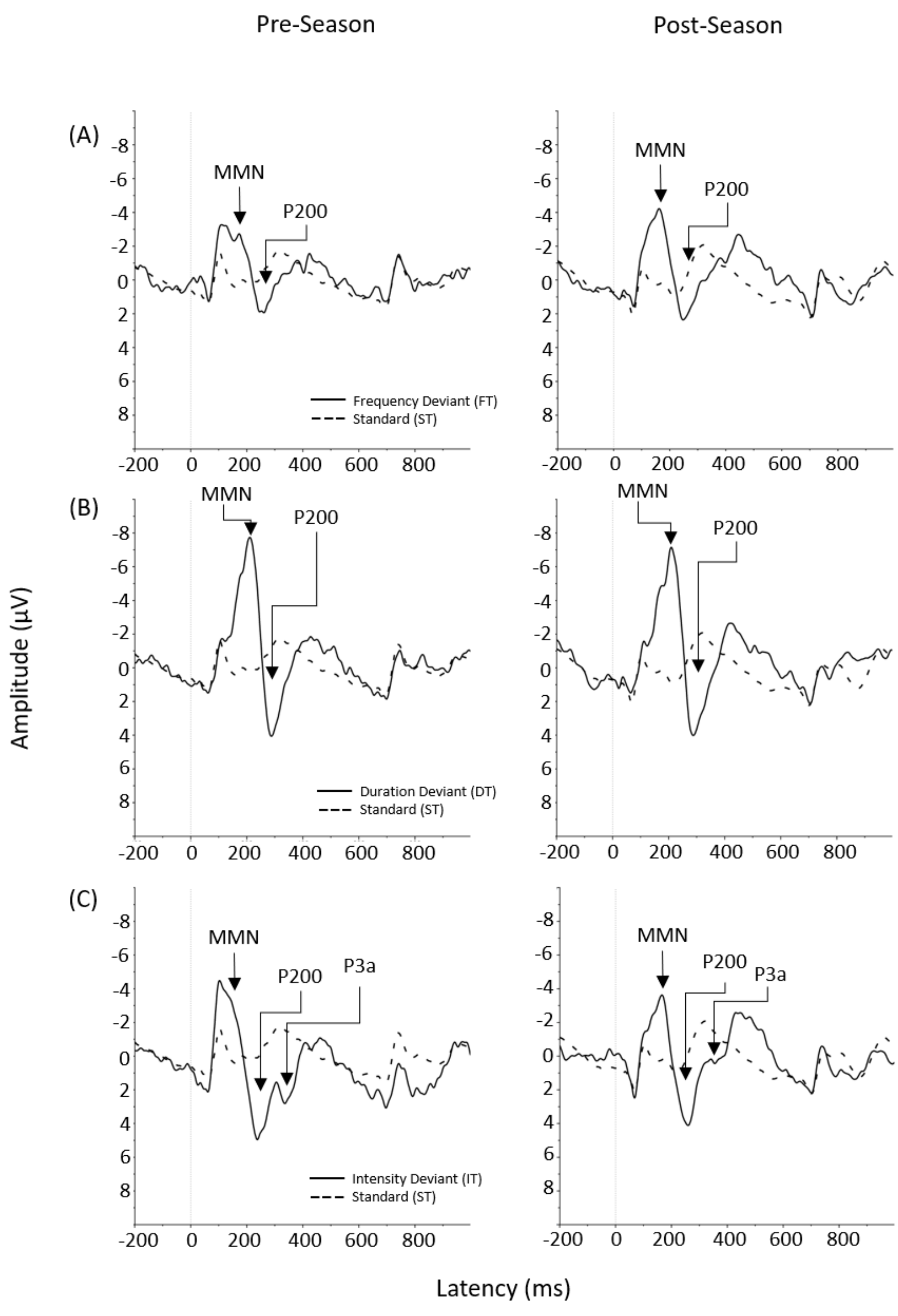

Figure 2: *Grand-averaged MMN protocol standard and deviant waveforms recorded at Cz for each group. Pre-season group: left; Post-season group: right. (A): MMN and P200 components evoked in the Frequency condition. (B): MMN and P200 components evoked in the Duration condition. (C): MMN, P200, and P3a components evoked in the Intensity condition.*

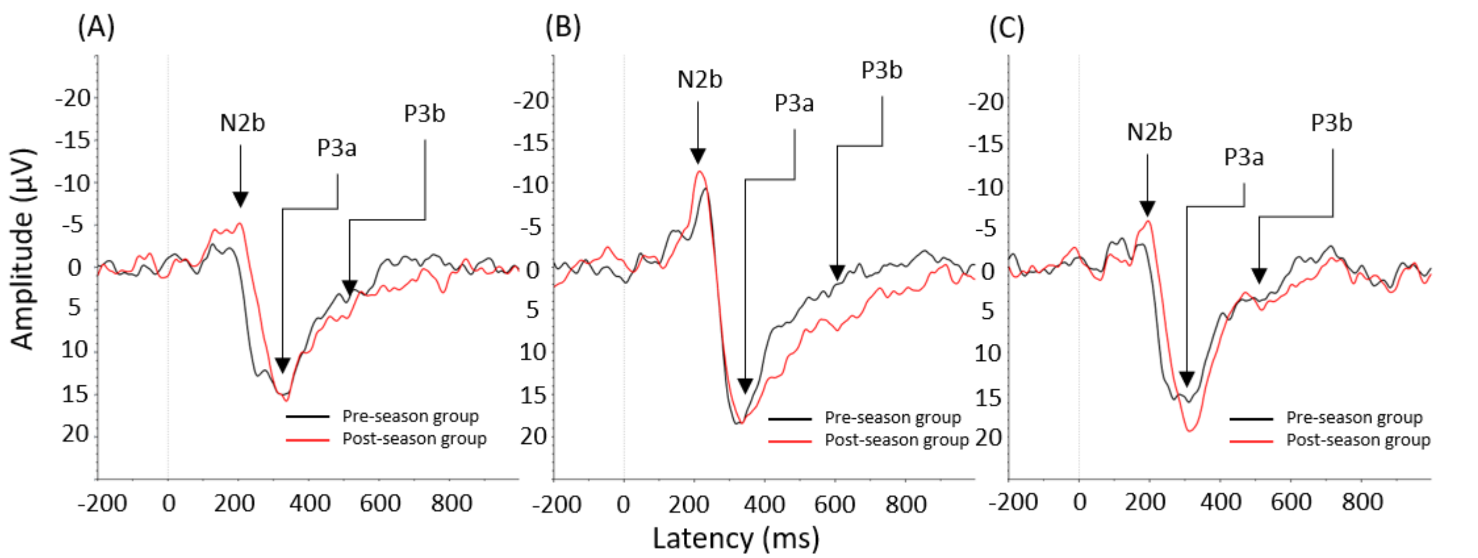

Figure 3: *Grand-averaged P300 protocol difference waveforms recorded at Cz for each group. Pre-season group: black; Post-season group: red. (A): N2b, P3a, and P3b components evoked in the Frequency condition. (B): N2b, P3a, and P3b components evoked in the Duration condition. (C): N2b, P3a, and P3b components evoked in the Intensity condition.*

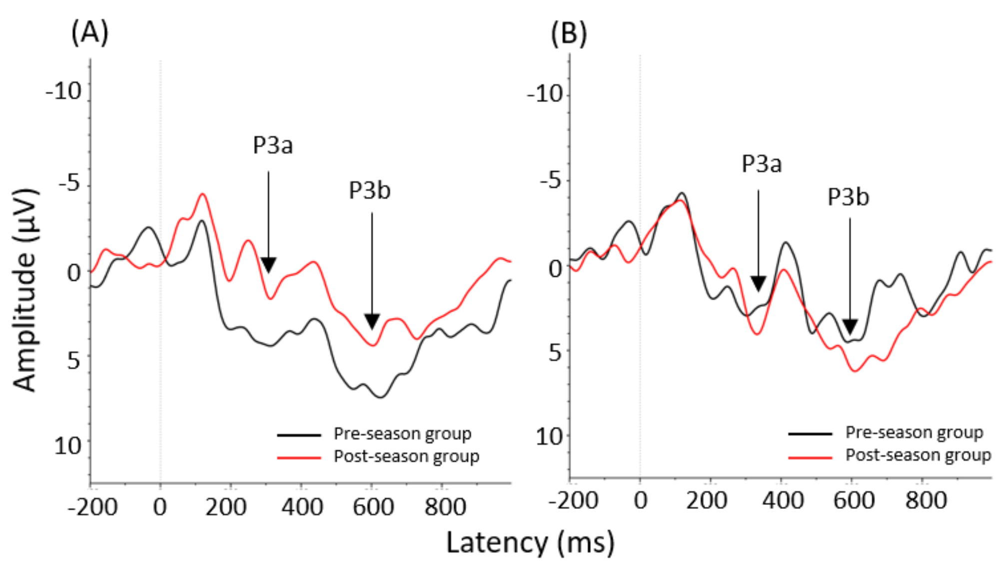

Figure 4: *Grand-averaged CVMT protocol waveforms recorded at Cz for each group. Pre-season group: black; Post-season group: red. (A): P3a and P3b components evoked in the Non-repeated condition. (B): P3a and P3b components evoked in the Repeated condition.*

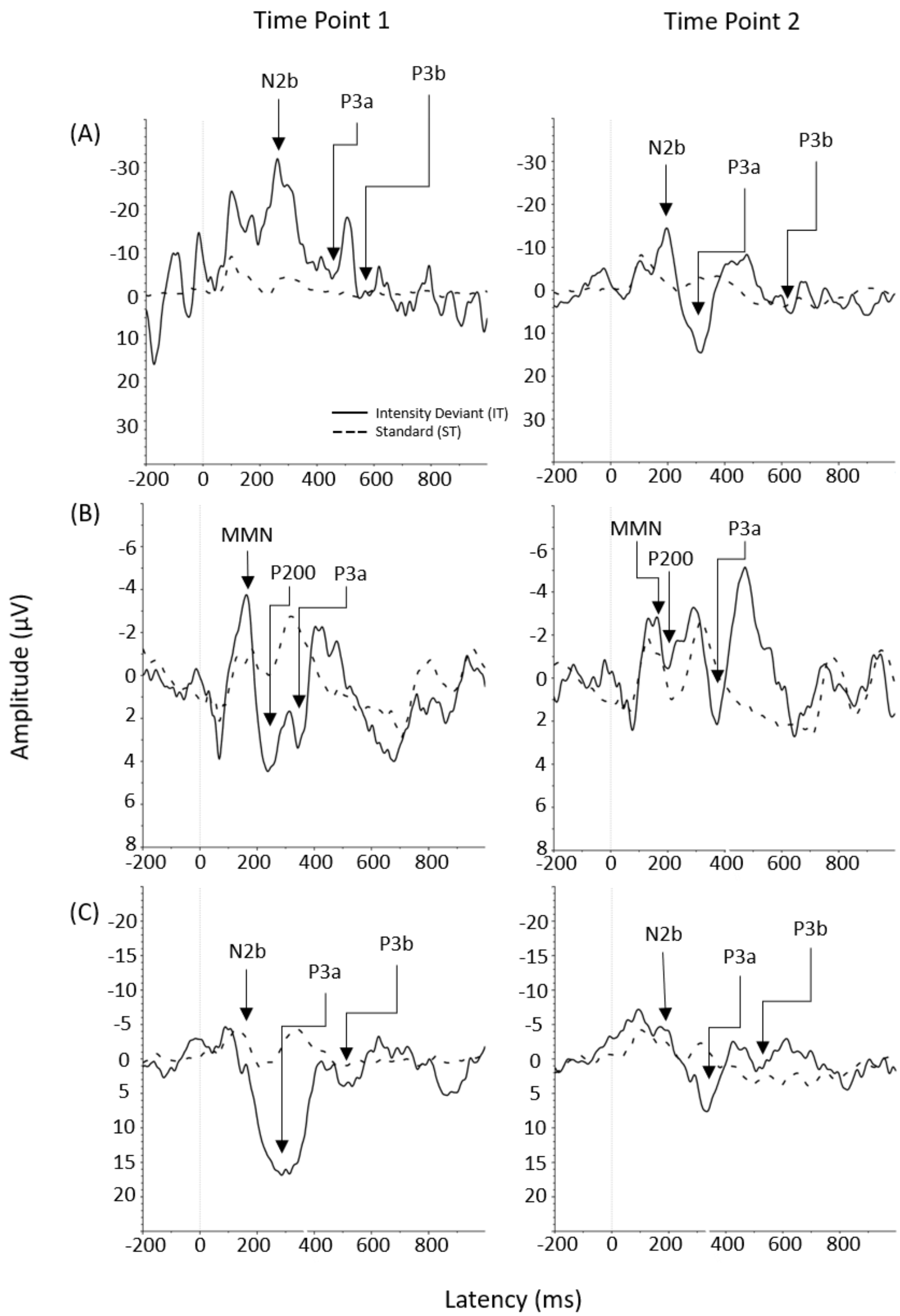

Figure 5*: Grand-averaged standard and deviant waveforms recorded at Cz for each significant case study effect. Time point 1: left; Time point 2: right. (A): N2b, P3a, and P3b for AW in the P300 protocol, Intensity condition; Time Point 1: post-concussion, Time Point 2: post-season. (B): MMN, P200, and P3a for BM in the MMN protocol, Intensity condition; Time Point 1: pre-season, Time Point 2: post-season. (C): N2b, P3a, and P3b for BM in the P300 protocol, Intensity condition; Time Point 1: pre-season, Time Point 2: post-season.*

3. Experiment 2

Experiment 2 addressed some of the issues in Experiment 1. Firstly, a control group consisting of non-contact sport athletes was included in order to better understand the effects of head and body contact, and ultimately subconcussive impacts on our measures of interest. Secondly, the sample size was increased to allow for a better understanding of group and individual differences in performance at baseline (pre-season) and post-season. Finally, we obtained a more extensive athletic and medical history, which made it possible to examine how various factors might have contributed to our findings.

3.1. Rationale and Objectives

3.1.1. Purpose

The purpose of Experiment 2 was to investigate changes in ERP characteristics due to subconcussive impacts in athletes involved in contact sports, and to understand how player position, in-game playing time, and concussion history might contribute to these findings.

3.1.2. Research Question and Hypotheses

There were two primary research questions in this experiment: 1) How is cognitive health, as detected by ERPs, affected in varsity football players across one season of play?, 2) Are there differences in various neurophysiological markers of cognitive function between contact athletes and non-contact athletes? We hypothesized that P3a and P3b ERP amplitudes would be attenuated post-season as compared to pre-season, and that these same ERPs would be attenuated in the contact group as compared to the non-contact group. The effects of all other ERP components were considered exploratory.

3.1.3. Objectives

1. To investigate ERP changes across a season of contact sports in a relatively homogeneous sample;
2. To investigate ERP differences between contact and non-contact athletes;
3. To further investigate the utility of the CVMT in understanding cognitive deficits due to subconcussive impacts;
4. To explore how factors affecting susceptibility to subconcussive impacts such as position and playing time, along with concussion history might contribute to these findings.

3.2. Methods

3.2.1. Participants

We recruited a total of 79 participants for this study (21 controls and 58 contact-sport athletes). The contact-sport athletes included members of McMaster University's varsity football team (mean age: 19.8, range: 18-23) tested at baseline (pre-season) and post-season. Both testing points took place at the onset of an academic term, thus minimizing the possibility of factors such as stress and depression levels during testing serving as a confound. Controls were age- and sex-matched athletes (all male) involved in non-contact sports including rock climbing, volleyball, swimming, squash, rowing, and running (mean age: 20, range: 18-25) with no history of concussion or any neurological disorder. The average time between pre- and post-season testing for contact athletes was 149.6 days (s=4.70). Contact athletes were tested on average 58.2 days (s=4.12) after their final game to accommodate the athletes' academic and athletic schedules. Controls were tested once during their sport's seasons in order to obtain a sufficient number of participants. The inclusion criteria were fluent English speakers, normal or corrected-to-normal vision, no history of hearing or speech/language problems, and no medications that act on the central nervous system. In accordance with inclusion/exclusion criteria, two controls and three contact-sport athletes were excluded because they were taking medications that act on the central nervous system at the time of testing. One control was excluded because of a history of concussion. Another three contact-sport athletes were excluded due to technical issues with one of their two recordings. Finally, 14 contact-sport athletes were lost post-season to attrition leaving a total of 18 controls and 38 contact sport athletes (see Figure 6 for details regarding inclusion/exclusion). All participants provided informed consent prior to participating in the experiment. Subjects were recruited through personal contacts in the Department of Athletics and Recreation, and postings around the McMaster University campus. This study was approved by the Hamilton Integrated Research Ethics Board (HIREB).

3.2.2. Procedure

The procedure in Experiment 2 was the same as that in Experiment 1 except that the computerized survey was modified to obtain a more extensive athletic and concussion history from all athletes, and the Edinburgh Handedness Inventory was excluded to reduce the duration of testing sessions. Given that source localization was not a goal of this study, there were no concerns about hemispheric asymmetries due to handedness.

3.2.3. Behavioural Tasks

Participants were administered several assessments prior to the EEG experiment, including the Beck Depression Inventory II (BDI-II), Short Form Health Survey (SF-36), Post Concussion Symptom Scale (PCSS), Perceived Stress Scale (PSS), and additional questions regarding athletic and concussion history through an online survey (see Appendices for questionnaires). The BDI-II, SF-36, PCSS, and PSS self-report tests were used to evaluate the overall health and well-being of participants. The BDI-II, specifically, was a means of assessing individual levels of depression (Beck, Steer, & Brown, 1996), while the SF-36 was an indicator of general health by evaluating measures such as vitality, physical functioning, emotionality, mental state, and general health perceptions (McHorney et al., 1993). The PCSS assessed symptom severity following a concussion as well as concussion-like symptoms in healthy individuals (Chen et al., 2007). Lastly, the PSS evaluated participants' self-reported stress levels (Cohen et al., 1983; Cohen, 1988).

3.2.4. EEG Stimuli and Experimental Conditions

The EEG stimuli and experimental conditions were identical to those in Experiment 1.

3.2.5. EEG Recordings

The process and equipment used for the electroencephalography recordings were identical to Experiment 1 except that one participant file was referenced offline to the nose rather than the mastoids due to a technical issue resulting in poor recordings for mastoid data. This was not expected to have any effects on the ERP characteristics of interest, namely amplitude and latency, as previous research has only suggested differences in topography across these two reference sites for our ERPs of interest (Naatanen & Näätänen, 1992; Yao et al., 2019). Where necessary, participants' EEG recordings were excluded due to insufficient data or poor quality EEG recordings. More specifically, if there was excessive jitter in the recording such that ERP components could not be differentiated from noise, either the entire EEG was discarded or the relevant paradigms were excluded (details to follow in the results section).

3.2.6. Behavioral Data Analysis

Group differences in ERP amplitude and latency across conditions of each paradigm were assessed using descriptive statistics and ANOVAs. Differences in amplitude were also evaluated across regions. In addition, regressions between behavioural data and EEG data were performed where a significant pre- to post-season effect was found in the contact group in an effort to associate factors such as concussion history and athletic history with the ERP components recorded in this study.

Statistical analysis of the PCSS, SF-36, BDI II, and PSS were conducted in R Studio 1.2.5033 using a one-way ANOVA assuming unequal variances. Statistical significance was considered at $p<0.05$.

3.2.7. EEG Data Analysis

The EEG data analyses were conducted similarly to Experiment 1. We evaluated differences between the non-contact group and the contact group at pre-season, as well as between the non-contact group and the contact group at post-season with the between factor of group at three levels (controls, pre-season, and post-season), and the within factor of condition at three levels (frequency, duration, and intensity), and of ROI at 9 levels. Since the pre-season and post-season groups consisted of the same participants, pre-season and post-season differences in ERPs were evaluated with the within factor of group at two levels (pre-season and post-season), the within factor of condition at three levels (frequency, duration, and intensity), and of ROI at 9 levels. All analyses were conducted using Greenhouse-Geisser corrected degrees of freedom where applicable (i.e. when the assumption of sphericity was violated). Analysis of latency did not include the within factor condition of ROI. Within the P300 protocol, peak analyses were conducted on mean amplitude for the N2b (175–275 ms), P3a (275–375 ms), and P3b (400–700 ms) ERP components for each condition. Peak analyses on mean amplitude within the CVMT protocol were conducted on the P3a (275–375 ms) and P3b (400–700 ms). Finally, peak analyses on mean amplitude within the MMN protocol were conducted for the MMN (150–250 ms). EEG analyses were conducted on the peak amplitude and latencies of the difference waves for each condition in the P300 and MMN (intensity, frequency, and duration), and on the peak amplitude and latencies of the averaged waveforms for each condition of the CVMT (non-repeated and repeated). All peak analyses were performed on the signed amplitude.

We also conducted a series of post hoc linear regressions of player position, playing time, and number of previous concussions on ERP characteristics where a pre- to post-season effect was found to better understand what other factors might contribute to these effects. Statistical analyses were performed for both amplitude and peak latency using mixed-effects analysis of variance (ANOVA).

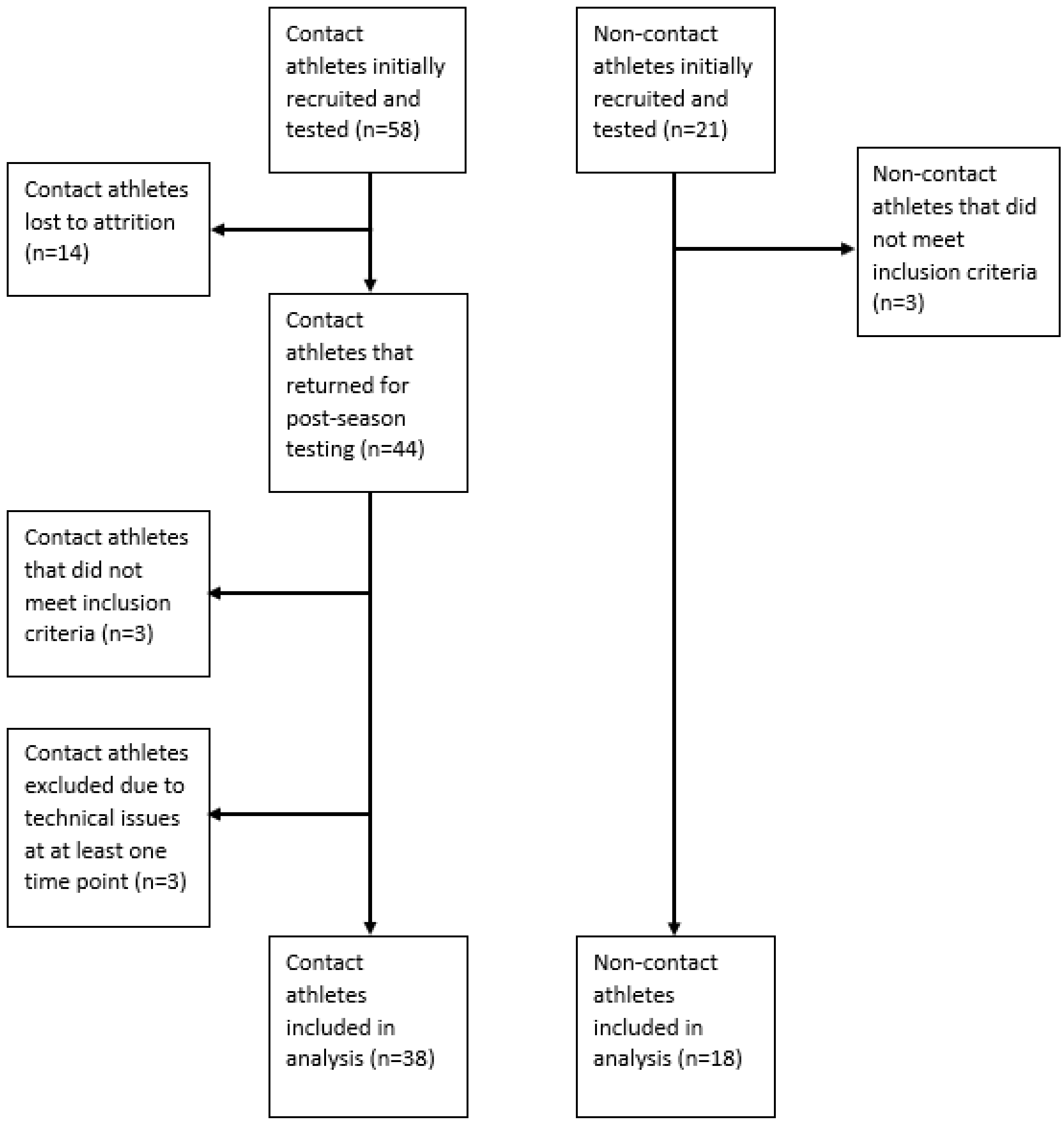

Figure 6: *Flow chart of inclusion/exclusion by group.*

3.3. Results

3.3.1. Demographic and Behavioural

Non-contact athletes were an average of 20 years old, while contact athletes were an average of 19.7 years old at the pre-season stage of testing. All participants were male as the football team consists of only male athletes and the controls were age- and sex-matched. The average number of previous concussions sustained in the contact group was 0.95 (range 0–4) and the average estimated in-game playing time was 290 minutes (range 0–3300). We tested football players in various positions including Defensive Back (n=3), Defensive Lineman (n=6), Fullback (n=1), Linebacker (n=3), Offensive Lineman (n=9), Quarterback (n=2), Running Back (n=5), Special Teams (n=3), and Wide Receiver (n=6). See Table 3 for an overview of the demographic data for the contact group.

All participants completed the BDI-II, SF-36 Short Form Survey, PSS, and PCSS after providing written informed consent.

The mean scores on the BDI-II in the contact group were 5.0 (s=4.3) at pre-season, 8.5 (s=7.0) at post-season, and 5.2 (7.4) for the non-contact group. The one-way ANOVA revealed a significant main effect of group ($F(2,91)=3.43$, $p<0.05$), and pairwise comparisons using Tukey's HSD revealed that the BDI-II score post-season was statistically higher than pre-season, meaning that the athletes experienced more depressive symptoms post-season than pre-season.

The SF-36 groups results were split into eight categories: physical functioning, role limitations due to physical health, role limitations due to emotional problems, energy/fatigue, emotional well-being, social functioning, pain, and general health. We ran a one-way ANOVA on each of the eight factors of the SF-36 and found significant group differences in social functioning ($F(2,91)=3.12$, $p<0.05$) and pain ($F(2,91)=3.91$, $p<0.05$). Post hoc pairwise comparisons using Tukey's HSD revealed that these effects were attributed to the non-contact group demonstrating lower scores in social functioning category and higher scores in the pain category than the contact group at pre-season. This can be interpreted as the non-contact group having lower social functioning compared to the contact athletes at pre-season, and the non-contact group experiencing less bodily pain than the contact athletes at pre-season.

The mean scores on the PCSS for the contact group at pre-season and post-season, and the non-contact group, respectively were 6.3 ($s=9.3$), 11.5 ($s=15.9$), and 8.6 ($s=13.5$). There were no significant differences in PCSS scores between the contact group at pre-season or at post-season, and the non-contact group.

Finally, the mean scores on the PSS for the contact group at pre-season and post-season, and the non-contact group, respectively were 18.9 ($s=3.2$), 18.4 ($s=3.4$), and 19.3 ($s=3.1$). There were no significant differences in PSS scores between the contact group at pre-season and post-season, and the non-contact group. See Table 4 for an overview of the behavioural results.

3.3.2. Neurophysiological Results

We examined group level differences in ERP characteristics for the following ERP components: MMN, N2b, P3a, and P3b. All differences in latency were examined using a two-way ANOVA with the independent variables being “group” and “condition,” whereas amplitude differences were examined using a three-way ANOVA with the independent variables being “group,” “condition,” and “region.” We used a mixed-effects ANOVA with “group” as a between-subjects variable to evaluate any overarching differences between the non-contact group and the contact athletes at pre-season, as well as between the non-contact group and the contact athletes at post-season. Since the pre-season and post-season groups consisted of the same participants, pre-season and post-season differences in ERPs were evaluated using a repeated-measures ANOVA. All analyses were conducted using Greenhouse-Geisser corrected degrees of freedom to correct for a lack of sphericity where applicable and to avoid inflating Type 1 error.

3.2.2.1. Comparing Contact and Non-Contact Athletes

The ERP component of interest in the MMN Oddball Paradigm was the MMN. One contact-sport athlete was excluded from the MMN analyses due to insufficient data or poor quality EEG recordings (experimental group n=37; control group n=18). There was a significant Group x Condition interaction for MMN latency ($F(4,178)=2.8$, $p<0.05$), which post hoc analyses revealed was attributable to a shorter MMN latency in the Intensity condition pre-season as compared to post-season; a comparison that is not relevant to these analyses and will be addressed in the within-subjects analyses. There was also a Group x Condition interaction for MMN amplitude

($F(4,178)=2.9$, $p<0.05$). Post hoc analyses revealed this interaction was attributable to a differential effect in the Duration condition such that MMN amplitude was greater in the non-contact group as compared to the contact group at both pre- and post-season (Figure 7, Figure 8).

The ERP components of interest in the P300 Oddball Paradigm were the P3a, P3b, and N2b. Three controls and two contact-sport athletes were excluded from analysis for this paradigm due to insufficient data or poor quality of recordings (experimental group n=36; control group n=15). The two-way mixed effects ANOVA revealed no group differences for P3a latency. However, the three-way mixed effects ANOVA for P3a amplitude revealed a significant main effect of group ($F(2,84)=5.5$, $p<0.05$) such that the P3a amplitude was smaller in the contact group at pre- and post-season as compared to the non-contact group, and a significant Group x Region interaction ($F(16,672)=2.3$, $p<0.05$), which post hoc analyses revealed was attributable to a smaller P3a amplitude in the contact group at pre-season and post-season as compared to the non-contact group at each of the parietal sites, central sites, and the left frontal site. There were no group differences in P3b latency, but there was a Group x Region interaction for P3b amplitude. Post hoc analyses revealed this interaction was attributable to a smaller P3b amplitude in the contact group at pre-season and post-season as compared to the non-contact group at each of the parietal sites. There was a Group x Region interaction for N2b amplitude, however this effect was not strong enough to survive post hoc analyses. There were no group differences in N2b latency. See Figure 9 for a visual representation of the ERP components in the P300 Oddball Paradigm.

The ERP components of interest in the CVMT Paradigm were the P3a and P3b. There were no group differences in P3a latency in this paradigm. However, there was a Group x Region interaction for P3a ($F(16, 728)=3.01$, $p<0.05$) and P3b amplitude ($F(16,728)=3.62$, $p<0.01$). Post hoc tests revealed that for the P3a this interaction was attributable to a smaller amplitude in the contact group at both pre- and post-season as compared to the non-contact group in all parietal regions as well as the mid-central region. For the P3b this interaction was due to a reduced P3b amplitude in the mid-parietal region in the contact group at both pre- and post-season as compared to the non-contact group. There was also a significant Group x Condition interaction for P3b latency ($F(2,91)=3.16$, $p=0.05$), however post hoc tests were not significant. See Figure 10 for a visual representation of the ERP components in the CVMT Paradigm.

See Table 5 for a summary of the between-subjects neurophysiological results.

3.2.2.2. Comparing Pre-season and Post-season Measures in Contact Athletes

The ERP components of interest in each paradigm were the same as those in the between-subjects design. In the MMN Oddball Paradigm we examined the MMN component. One participant was excluded from the MMN analyses due to insufficient data or poor quality EEG recordings ($n=37$). There was a significant Group x Condition interaction for MMN latency ($F(2,72)=4.9$, $p<0.05$), which post hoc analysis revealed to be driven by a shorter MMN latency in the contact group at post-season as compared to pre-season in the intensity condition (Figure 7, Figure 8). There were no group effects of MMN amplitude.

In the P300 Oddball Paradigm we examined the P3a, P3b, and N2b ERP components. Two participants were excluded from the analyses for the P300 paradigm due to insufficient data or poor quality EEG recordings (n=36). Statistical analysis revealed a Group x Condition interaction for P3a latency ($F(2,70)=3.14$, $p<0.05$). Post hoc analyses suggested that this interaction effect was driven by a shorter latency pre-season as compared to post-season specifically for the duration condition of the oddball task (Figure 9). There were no group effects of P3a amplitude, P3b latency or amplitude, or N2b latency or amplitude across time points in the contact group in the P300 Oddball Paradigm.

Finally, in the CVMT Paradigm we examined the P3a and P3b ERP components. There were no significant effects of P3a latency or amplitude in the contact group across time points. However, there was a Group x Condition interaction for P3b latency ($F(1,37)=7.1$, $p<0.05$), which post hoc analyses revealed was attributable to a delayed latency in the contact group at post-season as compared to pre-season in the Repeating condition (Figure 10). There were no group effects of P3b amplitude in this paradigm.

See table 6 for a summary of the within-subjects neurophysiological results.

3.3.3. Post Hoc Regression Analyses

We conducted a series of post hoc linear regressions to better understand the effects of playing time, concussion history, and player position on the differences in ERP characteristics that were detected in the contact group across timepoints, namely: P3b latency in the repeated condition of the CVMT paradigm, P3a latency in the duration condition of the P300 paradigm, and MMN latency in the intensity condition of the MMN paradigm. Playing time was defined as the total number of self-reported minutes an athlete spent on the football field in games and was, therefore, only evaluated in the contact group ate post-season; concussion history was defined as the total number of self-reported concussions sustained to date; and player position was defined as each athlete's primary playing position for the season. Positions were categorized as follows: Defensive Back (DB), Defensive Lineman (DL), Fullback (FB), Linebacker (LB), Offensive Lineman (OL), Quarterback (QB), Running Back (RB), Special Teams (ST), and Wide Receiver (WR). Due to the low number of athletes in each position, we grouped positions into most hits (OL, DL, and LB) , least hits (QB), and other (FB, RB, ST, WR, and DB) in accordance with findings from studies using the Head Impact Telemetry System providing metrics on hits in a season of play across football positions (Crisco et al., 2010; Crisco et al., 2011; Funk et al., 2012). We found that number of previous concussions was not associated with any of the alterations in ERP characteristics from pre- to post-season. However, this effect could be due to inaccuracies in the players' self-reported concussion histories as evidenced by differential reporting from pre- to post-season for numerous athletes. In-game playing time after one season was associated with MMN latency in the intensity condition for the MMN Oddball Paradigm such that increased playing time was associated with increased MMN latency in the contact group at post-season ($F(1,35)=23.8$, $p<0.001$), adjusted-$R^2=0.39$; Figure 11). Finally, player position correlated with both P3a latency in the duration condition of the P300 Oddball Paradigm ($F(2,69)=3.70$, $p<0.05$, adjusted-$R^2=0.07$; Figure 12) and P3b latency in the repeated condition of the CVMT ($F(2,73)=4.41$, $p<0.05$), adjusted-$R^2=0.083$; Figure 13). In both cases this association was such that players in positions expected to acquire the most hits had shorter ERP latencies as compared to players in the "Other" grouping. Player position was not associated with MMN latency in the intensity condition of the MMN Oddball Paradigm.

3.4. Discussion

In this study we recruited members of the McMaster varsity football team to be tested both at pre-season and post-season. Another group of non-contact athletes from various sports were included as a control. Participants completed behavioural questionnaires to evaluate their overall health as well as their athletic and concussion history and any concussion-related symptoms, then underwent an EEG recording while completing various computer tasks: the P300 Oddball Paradigm, the CVMT Paradigm, and the MMN Oddball Paradigm. The non-contact group reported less bodily pain and lower social functioning on the SF-36 than the experimental group at pre-season. These differences can likely be attributed to the experimental group's continued involvement in a high-contact sport, and the team-oriented nature of football as compared to more individualized, non-contact sports such as swimming and running. There were also statistically significant differences in self-reported depressions scores between in the contact group from pre-season to post-season such that they reported higher levels of depression at post-season, however both of these scores qualified as minimal depressive symptoms and would not qualify as clinical depression (Beck et al., 1996). Otherwise, we found no significant differences in behavioural scores between groups, suggesting that there were no underlying differences in concussion-related symptoms, stress levels, or overall health as assessed by the PCSS, PSS, and SF-36, respectively.

We conducted a number of analyses to better understand the neurophysiological effects of repeated subconcussive blows over the course of a season of collegiate football as assessed by ERP characteristics. The findings will be discussed by protocol.

3.4.1. P300 Paradigm

In the P300 Oddball Paradigm we found a reduced P3a amplitude in the contact group at both time points (pre- and post-season) as compared to the non-contact group across centro-parietal regions along with the same pattern in P3b amplitude across parietal regions. Given that many of these athletes had a history of concussion or at least of repeated impacts resulting in excessive force to the head, these results are consistent with findings that the P3a and P3b are associated with deficient stimulus discrimination and resource allocation and/or working memory, respectively, following a concussion (Dupuis et al., 2000; Bernstein, 2002; De Beaumont et al., 2007; Baillargeon et al., 2012; Ruiter et al., 2019; Ruiter et al., 2020). However, what is of greater interest is that there was no difference in reported concussion symptoms across groups, suggesting that the P3a and P3b ERP components are sensitive to cognitive changes even in the absence of symptoms (Dupuis et al., 2000; Baillargeon et al., 2012). We also observed a shortened P3a latency at post-season as compared to pre-season in the contact group to the duration deviant, suggesting that a season of football may have resulted in alterations in attentional processing (Johnson et al., 2004; Polich, 2007). This was an unusual finding as a shorter ERP latency is typically associated with increased processing speed and therefore healthier cognitive functioning. However, one possible explanation for this finding emerges from research that suggests a perceived alteration in P3a latency can sometimes be attributed to an alteration in P3a amplitude as demonstrated by dipole-based source analysis (Elting et al., 2005). Thus, conventional ERP analyses may not offer reliable results regarding differences in P3a latency between groups. This change in P3a latency across the season correlated with player position groupings of expected high frequency, low frequency, and variable frequency (“Other”) head impacts (Crisco et al., 2010; Crisco et al., 2011; Funk et al., 2012), suggesting that frequency of hits may partially account for variation in the effects of subconcussive blows, however the direction of this effect was not as expected. The correlation was such that a higher expected frequency of hits was in line with a shorter P3a latency. It is possible that this result is in fact attributable to the magnitude of these hits rather than the frequency. Research involving the magnitude and frequency of head impacts across varying positions in collegiate football has revealed that for some of those who sustain the most hits, these hits are often less forceful (Crisco et al., 2011; Funk et al., 2012). Thus, this result may indicate that more forceful head impacts result in a delayed P3a, suggesting delayed cognitive processing.

3.4.2. CVMT Paradigm

The results of the CVMT somewhat mimicked those of the P300 Oddball Paradigm in that we found a reduced P3a and P3b amplitude in the contact group at both time points (pre- and post-season) as compared to the non-contact group across parietal regions. This would suggest that cumulative exposure to subconcussive impacts may have resulted in poorer stimulus discrimination and resource allocation. Again, an interesting and informative finding given the lack of concussion symptoms and concussion diagnosis at both time points. This reduction in P3a and P3b amplitude in the absence of a current concussion offers support for the persistent effects of cumulative head impacts (De Beaumont et al., 2009; Ruiter et al., 2019). Further support for the significance of these impacts can be seen from the observed delay in P3b latency in the Repeated condition following a season of involvement in a high-contact, collision sport. A delay in P3b latency suggests an increase in stimulus processing time. This change in P3b latency across the season correlated with player position groupings of expected high frequency, low frequency, and variable frequency ("Other") head impacts (Crisco et al., 2010; Crisco et al., 2011; Funk et al., 2012), suggesting that frequency of hits may partially account for variation in the effects of subconcussive blows. As with the P3a in the P300 Oddball Paradigm, the direction of this effect was not as expected. The association was such that a higher expected frequency of hits was in line with a shorter P3b latency. However, again it is worth noting that in many cases the players expected to acquire the least hits tend to sustain higher magnitude hits, whereas the players sustaining less hits tend to experience impacts of a lower caliber (Crisco et al., 2011; Funk et al., 2012). Thus, this result should be considered both from the perspective of frequency and magnitude of head impacts. This result may indicate that more forceful head impacts result in a delayed P3b.

3.4.3. MMN Paradigm

In the MMN Oddball Paradigm we found a reduced MMN amplitude in the contact group at both time points (pre- and post-season) specifically to the duration deviant suggesting deficient pre-attentive processing and/or predictive coding as a result of cumulative exposure to subconcussive blows. Previous research involving the effects of concussion on the MMN have shown varied results. A study in adolescents found no differences in MMN characteristics between recently concussed adolescents and healthy controls (Ruiter et al., 2020), whereas a similar study involving retired football athletes who had sustained their most recent concussion on average 28 years prior to testing found a reduced MMN amplitude in these previously concussed athletes as compared to healthy age-matched controls (Ruiter et al., 2019). These two studies employed the same paradigms to assess this effect, therefore the discrepancy in results can likely be attributed to other factors (Boshra et al., 2020). One such factor might be involvement in the sport. Adolescents would have had relatively little experience in football relative to retired professional athletes, or even collegiate athletes such as those in the present study. Taken together, the results of the present study and of recent work suggest that perhaps the MMN is sensitive to lasting and more chronic deficits associated with concussion and subconcussive impacts. Finally, we found an unexpected reduction in MMN latency from pre-season to post-season in the contact group. Typically a shorter ERP latency is associated with increased processing speed and therefore healthier cognitive functioning. However, that interpretation is not likely to explain our findings given that these athletes were subjected to repeated subconcussive blows throughout the season. One possible explanation for this finding is that this shortened latency may indicate dysfunctional (i.e., inadequate) processing of these stimuli and therefore errors in integrating this information into neuronal networks (Grzella et al., 2001). Furthermore, in considering the ERP values of the contact group at post-season only it was found that increased playing time was associated with increased MMN latency. Since playing time was meant to provide one estimate of frequency of subconcussive blows, these findings suggest that there is a dose-response relationship between subconcussive blows and changes in measures sensitive to automatic attentional processes (Näätänen et al., 1993).

Taken together, these results suggest that repeated subconcussive blows can result in cognitive alterations that can be detected by ERP components. Our findings suggest that automatic attention, reactive attention, resource allocation and possibly working memory were all affected by participation in one season of collegiate football despite the absence of concussion within this time frame. Furthermore, this study revealed differences in ERP characteristics in a group of non-contact athletes as compared to a group of contact athletes even at baseline, thus offering evidence for persistent cognitive effects resulting from repeated head and body impacts including concussion and subconcussive blows. These findings can be seen as compatible with other work suggesting that differences across dimensions of age, extent of exposure to head/brain trauma, and the passage of time since injury can be interpreted within a model of acute-to-chronic progression that is time-dependent and non-linear (Boshra et al., 2019; Boshra et al., 2020). This model, based on recent functional connectivity analysis of an active attentional task, incorporates a neural resources factor as a mechanism that can explain the non-linearity of the progression. What these current data suggest is that the phenomenon is reflected not only at the level of active attentional resource usage but also at a more fundamental level of “automatic” attention or low level predictive coding mechanisms (Garrido et al., 2007; Garrido et al., 2009).

This study was not without limitations. Firstly, all athletes in this study were male because tackle football is not offered for females and the control group was age- and sex-matched to the experimental group. This limits the generalizability of our results especially given the differences in reported concussions between males and females (Gessel et al., 2007; for a review see Dick, 2009). Another limitation is that concussion history was self-reported and was clearly reported inconsistently as evidenced by some athletes reporting a reduced number of concussions from pre- to post-season. We also did not directly measure frequency and magnitude of head impacts, but rather we made assumptions based on literature using accelerometers, thus limiting our interpretations of our findings in relation to these metrics. Finally, we tested fairly long after the football season ended to accommodate the athletes’ academic schedules. Previous studies were able to conduct neuropsychological testing within three weeks of the team's final game (Miller et al., 2007; Gysland et al., 2012; Marchesseault et al., 2018), whereas we tested over one month after the final game. Our testing may not have captured any transient effects of repeated head impacts, suggesting that our results could be interpreted as lingering effects.

Table 3: *Contact group demographics. Note: age refers to the player's age in years at the start of the season. Previous concussions refers to number of concussions reported prior to this season. Position is the player's primary position. Playing time refers to estimated in-game playing time this season.*

Player Demographics				
Player	Age (years)	Previous Concussions	Position	Playing Time (min)
1	18	1	Defensive lineman	0
2	18	1	Wide receiver	0
3	18	4	Defensive back	12
4	19	1	Defensive back	330
5	20	1	Offensive lineman	270
6	19	0	Wide receiver	90
7	19	0	Offensive lineman	2400
8	18	1	Offensive lineman	45
9	20	2	Quarterback	660
10	23	0	Defensive lineman	220
11	23	2	Defensive lineman	0
12	20	0	Defensive lineman	9
13	18	1	Running back	0
14	18	0	Defensive lineman	0
15	19	2	Offensive lineman	0
16	22	4	Offensive lineman	0
17	19	0	Linebacker	0
18	19	0	Defensive back	2
19	20	0	Special teams	38
20	19	2	Wide receiver	0
21	20	0	Offensive lineman	3300
22	21	4	Offensive lineman	180
23	18	1	Linebacker	180
24	19	1	Linebacker	300
25	23	0	Offensive lineman	30
26	22	0	Special teams	30
27	23	1	Defensive lineman	1000
28	21	0	Running back	600
29	18	2	Running back	100
30	21	2	Fullback	120
31	20	4	Running back	30
32	19	0	Running back	0
33	19	2	Quarterback	0
34	19	1	Wide receiver	0
35	19	1	Offensive lineman	15
36	22	1	Special teams	60
37	18	2	Wide receiver	0
38	18	3	Wide receiver	1000
Average	19.7	0.95	N/A	290

Table 4: *Between-group differences in the behavioural scores on the BDI-II, PCSS, PSS, and SF-36.*

Behavioural Scores						
Assessment	Control Mean (SD)	Pre-season Mean (SD)	Post-season Mean (SD)	*df*	*F*	*p*
Beck's Depression Inventory II (BDI-II)*	5.22 (7.38)	5.02 (4.34)	8.47 (7.01)	91	3.43	< 0.05*
Post Concussion Symptom Scale (PCSS)	8.61 (13.50)	6.26 (9.34)	11.47 (15.86)	91	1.50	> 0.05
Perceived Stress Scale (PSS)	19.28 (3.08)	18.95 (3.16)	18.45 (3.38)	91	0.46	> 0.05
Short Form Survey (SF-36)						
Category						
Physical functioning	99.17 (2.57)	96.71 (7.56)	98.82 (3.17)	91	1.98	> 0.05
Role lim. due to physical health	88.89 (26.04)	92.10 (21.04)	92.76 (20.06)	91	0.20	> 0.05
Role lim. due to emotional problems	81.48 (34.72)	95.61 (13.80)	82.96 (27.54)	91	2.48	> 0.05
Energy/fatigue	58.61 (22.67)	59.08 (17.97)	58.03 (17.46)	91	0.03	> 0.05
Emotional well-being	73.33 (18.30)	78.95 (13.24)	78.53 (13.59)	91	1.02	> 0.05
*Social functioning**	84.03 (21.35)	94.41 (9.50)	88.16 (17.18)	91	3.12	< 0.05*
*Pain**	90.28 (7.12)	79.08 (14.01)	81.97 (16.16)	91	3.91	< 0.05*
General health	82.78 (13.53)	77.63 (16.83)	72.37 (17.07)	91	2.62	> 0.05

Note: ":" denotes an interaction
*significance p ≤ 0.05

Table 5: *Between-group differences in P3a, P3b, and N2b amplitude and latency within the P300 protocol, P3a and P3b amplitude and latency within the CVMT*

P300 Protocol

P3a Amplitude			
Effect	*df*	*F*	*p*
Group**	84	5.46	< 0.01**
Group:Condition	168	0.63	> 0.05
Group:Region*	672	2.34	< 0.05*
P3a Latency			
Effect	*df*	*F*	*p*
Group	84	0.88	> 0.05
Group:Condition	168	1.67	> 0.05
P3b Amplitude			
Effect	*df*	*F*	*p*
Group	84	2.44	> 0.05
Group:Condition	168	1.26	> 0.05
Group:Region**	672	2.94	= 0.01**
P3b Latency			
Effect	*df*	*F*	*p*
Group	84	0.79	> 0.05
Group:Condition	168	0.38	> 0.05
N2b Amplitude			
Effect	*df*	*F*	*p*
Group	84	0.19	> 0.05
Group:Condition	168	0.93	> 0.05
Group:Region*	672	2.32	< 0.05
N2b Latency			
Effect	*df*	*F*	*p*
Group	84	0.87	> 0.05
Group:Condition	168	0.72	> 0.05

CVMT Protocol

P3a Amplitude			
Effect	*df*	*F*	*p*
Group	91	2.57	> 0.05
Group:Condition	91	0.77	> 0.05
Group:Region*	728	3.01	< 0.05*
P3a Latency			
Effect	*df*	*F*	*p*
Group	91	2.25	> 0.05
Group:Condition	91	0.67	> 0.05
P3b Amplitude			
Effect	*df*	*F*	*p*
Group	91	0.48	> 0.05
Group:Condition	91	1.59	> 0.05
Group:Region**	728	3.62	< 0.01**
P3b Latency			
Effect	*df*	*F*	*p*
Group	91	0.80	> 0.05
Group:Condition*	91	3.16	= 0.05*

MMN Protocol

MMN Amplitude			
Effect	*df*	*F*	*p*
Group	89	1.52	> 0.05
Group:Condition*	178	2.94	< 0.05*
Group:Region	712	1.25	> 0.05
MMN Latency			
Effect	*df*	*F*	*p*
Group	89	0.67	> 0.05
Group:Condition*	178	2.77	< 0.05*

Note: ":" denotes an interaction
*significance $p \leq 0.05$
**significance $p \leq 0.01$

Table 6: *Within-group differences in P3a, P3b, and N2b amplitude and latency within the P300 protocol, P3a and P3b amplitude and latency within the CVMT protocol, and MMN*

P300 Protocol				**CVMT Protocol**				**MMN Protocol**			
P3a Amplitude				***P3a Amplitude***				***MMN Amplitude***			
Effect	*df*	*F*	*p*	*Effect*	*df*	*F*	*p*	*Effect*	*df*	*F*	*p*
Group	35	0.52	> 0.05	Group	37	3.44	> 0.05	Group	36	1.24	> 0.05
Group:Condition	70	0.97	> 0.05	Group:Condition	37	1.39	> 0.05	Group:Condition	72	2.10	> 0.05
Group:Region	280	1.15	> 0.05	Group:Region	296	1.05	> 0.05	Group:Region	288	0.42	> 0.05
P3a Latency				***P3a Latency***				***MMN Latency***			
Effect	*df*	*F*	*p*	*Effect*	*df*	*F*	*p*	*Effect*	*df*	*F*	*p*
Group	35	0.00	> 0.05	Group	37	2.12	> 0.05	Group	36	1.43	> 0.05
Group:Condition*	70	3.14	< 0.05*	Group:Condition	37	0.48	> 0.05	Group:Condition*	72	4.87	< 0.05*
P3b Amplitude				***P3b Amplitude***							
Effect	*df*	*F*	*p*	*Effect*	*df*	*F*	*p*				
Group	35	2.50	> 0.05	Group	37	0.20	> 0.05				
Group:Condition	70	0.40	> 0.05	Group:Condition	37	1.53	> 0.05				
Group:Region	280	0.30	> 0.05	Group:Region	296	1.76	> 0.05				
P3b Latency				***P3b Latency***							
Effect	*df*	*F*	*p*	*Effect*	*df*	*F*	*p*				
Group	35	0.04	> 0.05	Group	37	0.47	> 0.05				
Group:Condition	70	0.22	> 0.05	Group:Condition*	37	7.12	< 0.05*				
N2b Amplitude											
Effect	*df*	*F*	*p*								
Group	35	1.00	> 0.05								
Group:Condition	70	0.16	> 0.05								
Group:Region	280	0.77	> 0.05								
N2b Latency											
Effect	*df*	*F*	*p*								
Group	35	1.35	> 0.05								
Group:Condition	70	1.50	> 0.05								

Note: ":" denotes an interaction
*significance $p \leq 0.05$

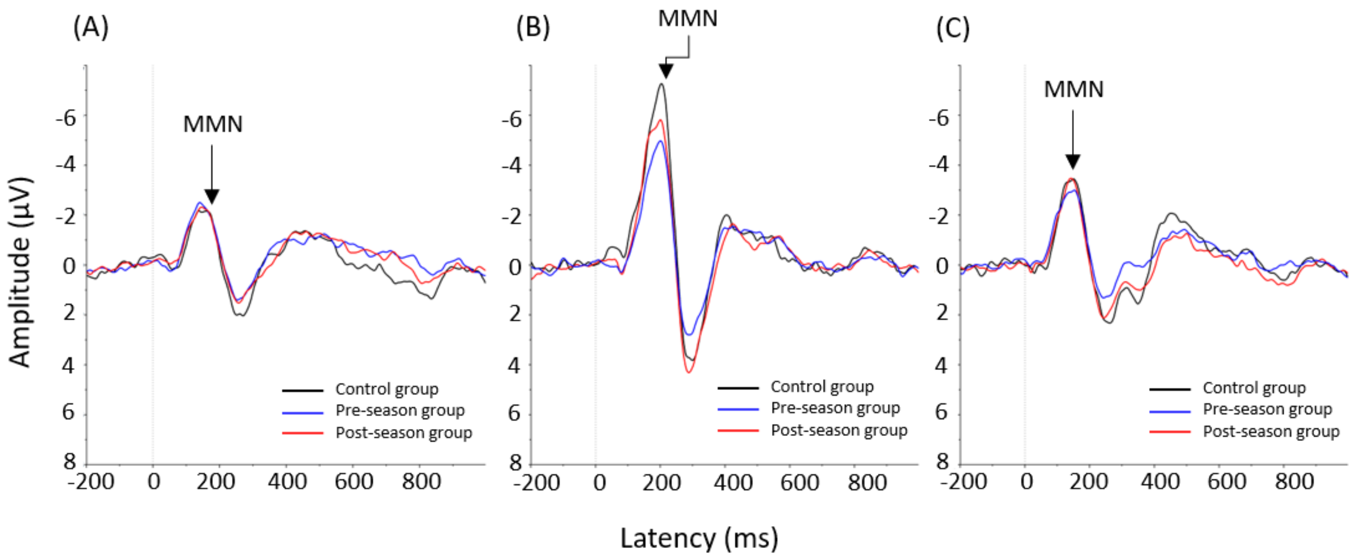

Figure 7: *Grand-averaged MMN protocol difference waveforms recorded at Cz for each group. Control group: black; Experimental group at pre-season: blue; Experimental group at post-season: red. (A): MMN component evoked in the Frequency condition. (B): MMN component evoked in the Duration condition. (C): MMN component evoked in the Intensity condition.*

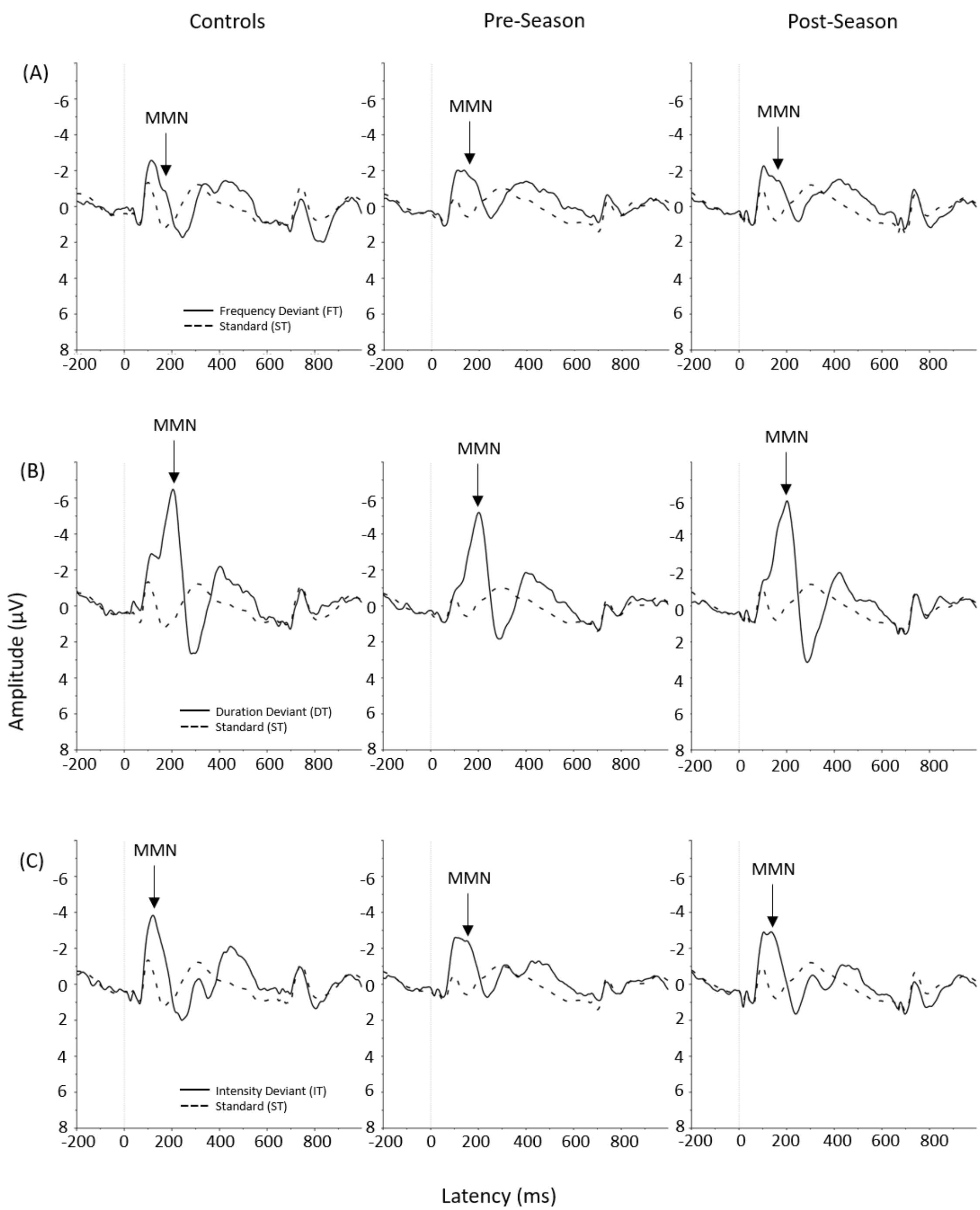

Figure 8: *Grand-averaged MMN protocol standard and deviant waveforms recorded at Cz for each group. Control group: left; Experimental group at pre-season: centre; Experimental group at post-season: right. (A): MMN component evoked in the Frequency condition. (B): MMN component evoked in the Duration condition. (C): MMN component evoked in the Intensity condition.*

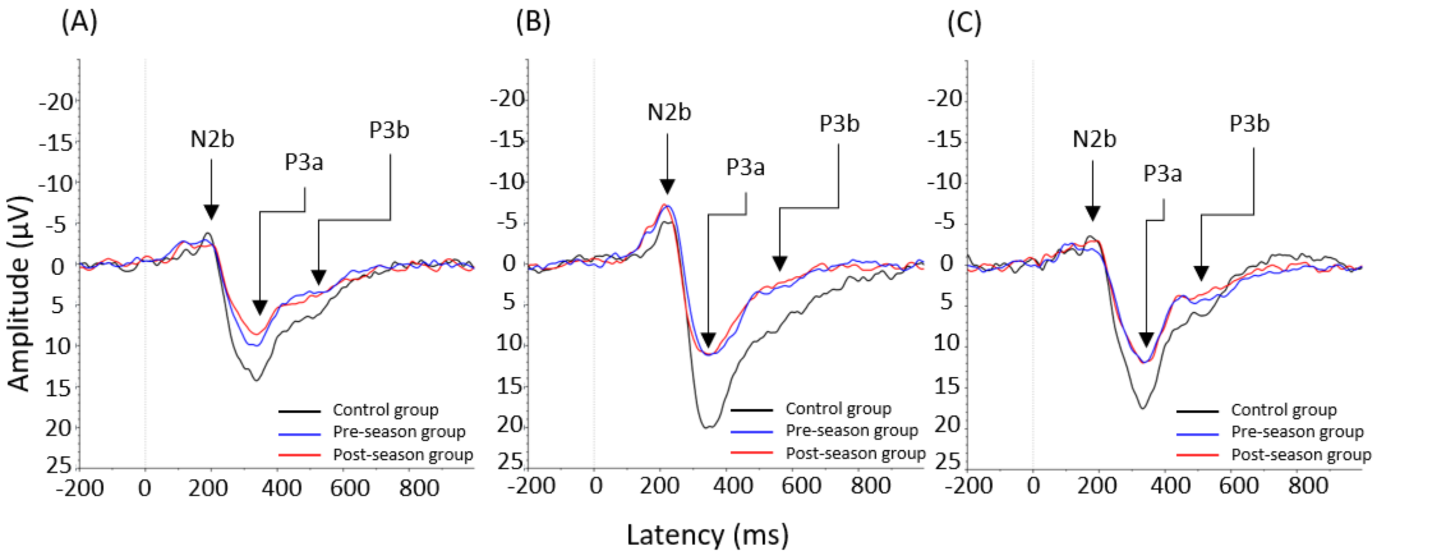

Figure 9: *Grand-averaged P300 protocol difference waveforms recorded at Cz for each group. Control group: black; Experimental group at pre-season: blue; Experimental group at post-season: red. (A): N2b, P3a, and P3b components evoked in the Frequency condition. (B): N2b, P3a, and P3b components evoked in the Duration condition. (C): N2b, P3a, and P3b components evoked in the Intensity condition.*

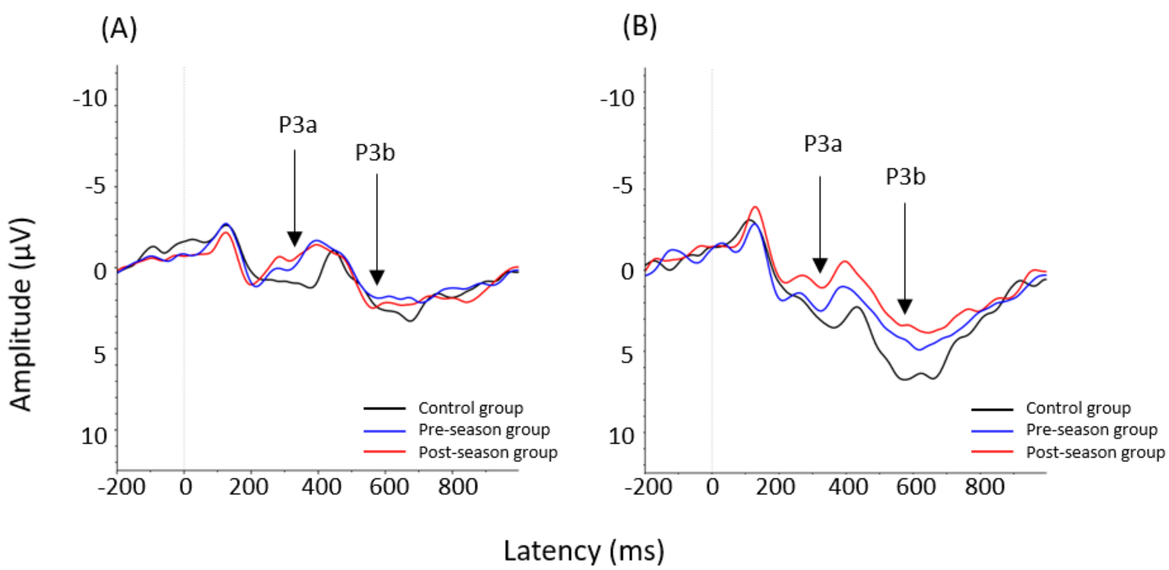

Figure 10: *Grand-averaged CVMT protocol waveforms recorded at Cz for each group. Control group: black; Experimental group at pre-season: blue; Experimental group at post-season: red. (A): P3a, and P3b components evoked in the Non-repeated condition. (B): P3a, and P3b components evoked in the Repeated condition.*

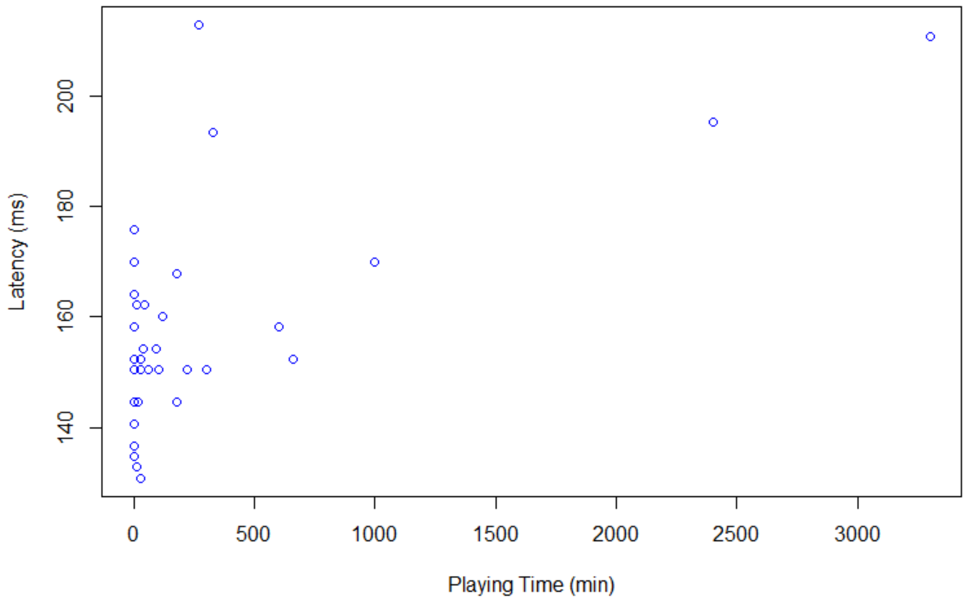

Figure 11: *Relationship between playing time and MMN ERP latency in the MMN protocol.*

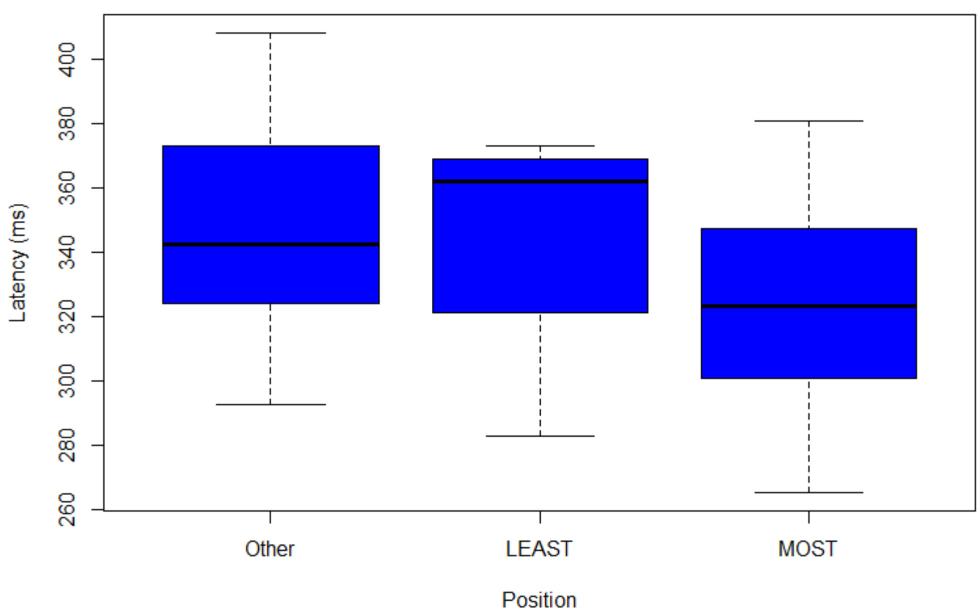

Figure 12: *Relationship between player position and P3a ERP latency in the P300 protocol. Player position grouped into MOST hits, LEAST hits, and Other. Groupings were as follows: MOST: offensive linemen, defensive linemen, and linebackers; LEAST: quarterbacks; and Other: fullbacks, running backs, special teams, wide receivers, and defensive backs.*

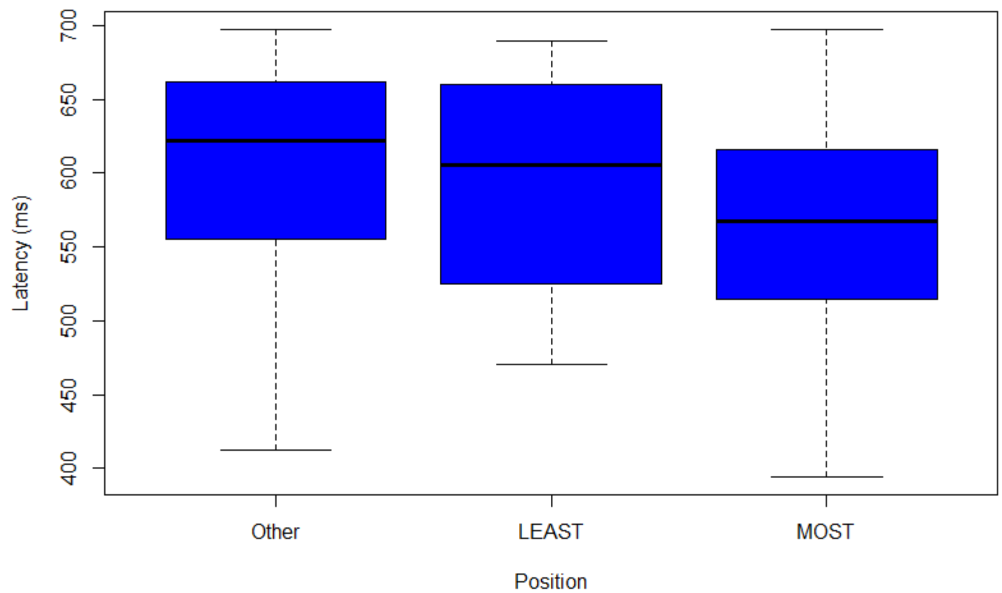

Figure 13: *Relationship between player position and P3b ERP latency in the CVMT protocol. Player position grouped into MOST hits, LEAST hits, and Other. Groupings were as follows: MOST: offensive linemen, defensive linemen, and linebackers; LEAST: quarterbacks; and Other: fullbacks, running backs, special teams, wide receivers, and defensive backs.*

4. General Discussion

The present study offers insight into the cognitive effects of both concussions and subconcussive impacts, and the utility of ERP components in detecting such effects. The study replicates findings suggesting 1) that high contact athletes have attenuated P300 components as compared to low contact athletes (Wilson et al., 2015; Moore et al., 2017), and, 2) that subconcussive impacts in a high contact sport across one season of play can alter P300 characteristics (Brooks, 2016). More interestingly, however, these are the first findings to suggest that factors such as playing time and a player's primary position are associated with changes in ERP characteristics across a season of play. This is also the first study to evaluate visual memory and passive predictive coding and attention in this sample. The novel finding that the P3b was generally delayed (in one condition) from pre-season to post-season demonstrates that visual memory is sensitive to subtle changes in an athlete's cognitive functioning as the result of subconcussive impacts. While the novel finding of a reduced MMN amplitude in the contact group compared to the non-contact group suggests that involvement in such high contact sports can have lasting effects on automatic attention, which is in line with a study on retired football players who were compared to healthy, age-matched controls (Ruiter et al., 2019).

A large body of research has been devoted to better understanding both the acute and chronic cognitive effects of concussions over the past several decades. However, until quite recently limited research had considered the effects of subconcussive impacts – blows to the head and/or body that do not result in a clinical diagnosis of concussion. Data recorded from the HIT System and other accelerometers have demonstrated that collegiate football players can sustain upwards of 1000 head impacts exceeding 10g of force over the course of one season of play (Crisco et al., 2010; Crisco et al., 2011). In considering the frequency and magnitude of these impacts as well as the long-term consequences associated with repeated head impacts, it is no surprise that there has been a growing concern for the role of these subclinical blows in altering cognitive processes.

Research involving neuropsychological evaluations of the cognitive effects of subconcussive impacts has produced mixed results. A study by Tsushima et al. (2019) used the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) protocol to compare neuropsychological test performance in high school athletes in high, moderate, and low contact sports. Their findings suggest that due to the high frequency of subconcussive impacts sustained in high contact sports, these athletes have impaired performance in several categories of cognitive functioning. In a separate study of high school athletes, it was also found that contact athletes demonstrated delayed reaction times and processing speeds as compared to non-contact athletes (Tsushima et al., 2016). However, a similar study involving the ImPACT and the Standardized Assessment of Concussion (SAC) found that following a season of collegiate football, athletes showed improved or similar ImPACT and SAC scores as compared to their pre-season measures (Miller et al., 2007). Similar results were seen in a study of collegiate men’s lacrosse players after a season of play, as they reported improved performance on the

Comprehensive Trail Making Test (CTMT) as the season progressed (Marchesseault et al., 2018). Finally, Gysland et al. (2012) conducted pre- and post-season testing on collegiate football players using several neuropsychological batteries in conjunction with the HIT System and found improved balance and increased concussion-like symptom count over a season of play. What was interesting, however, is that these results were predicted by various other factors such as number of previous concussions, years of collegiate play, and severity of impacts. These novel findings suggest that in order to disentangle the effects of subconcussive impacts in sports, we must also consider variables that could contribute to altered physiology and, therefore, changes in brain function. As such, the researchers suggested that future work investigating subconcussive impacts in sports should consider a potential dose-response relationship over a player's career (Gysland et al., 2012). A higher frequency of subconcussive impacts and concussions in one's career is likely to be associated with more adverse outcomes.

Given the inconsistencies in results across studies using neuropsychological testing, and the knowledge that electrophysiological measures are sensitive to subtle cognitive changes, recent work has shifted its focus towards using EEG to investigate effects of subconcussive impacts. Numerous studies have demonstrated the utility of ERP components in differentiating between individuals with and without a history of concussion (Dupuis et al., 2000; De Beaumont et al., 2007; Broglio et al., 2009; De Beaumont et al., 2009; Baillargeon et al., 2012; Ruiter et al., 2019; Ruiter et al., 2020). Several researchers were interested in whether these subtleties could also be detected following cumulative subconcussive impacts. In a study by Wilson et al. (2014) it was found that when comparing a group of previously concussed football players to their counterparts with no history of concussion as well as a group of non-contact athletes, the concussed group showed a reduced P3b amplitude to an auditory oddball with a visual distractor as compared to the other two groups. However, no difference in P3b amplitude was found between the two groups of football players. In a follow-up study that assessed seven collegiate football players at both pre- and post-season, Wilson et al. (2015) found no change in P3b amplitude. However, they did find a difference in P3b amplitude between the first years and the upper years, suggesting that perhaps P3b amplitude is sensitive to cumulative effects over time, but not within a season of play. This result is in line with our finding of no change in P3b amplitude across a season of play, but a significant difference in amplitude at baseline between contact and non-contact athletes. Since upper year students would presumably have more experience in collegiate football, it can also be assumed that they would have accumulated more head impacts than the first years. Thus, the upper year vs lower year comparison is similar to the contact vs non-contact comparison such that upper years, like contact athletes, would have sustained more head and body impacts than first years and non-contact athletes. Most recently, Moore et al. (2017) attempted to delineate the independent contribution of concussive and subconcussive impacts on neurophysiology using a three-stimulus visual oddball task in collegiate football players. They found attenuated N1 amplitude in the concussed group compared to a group of contact athletes with no concussion history and a non-contact group. They also found an attenuated P3a and P3b amplitude in the concussed and subconcussive group relative to non-athletes, suggesting that the concussed and subconcussive groups were virtually indistinguishable despite the lack of clinical presentation of a concussion in the subconcussive group.

These preliminary findings offer mixed evidence regarding the utility of ERPs in detecting subtle cognitive changes due to subconcussive impacts, however it is worth noting that the modalities across studies were varied and, unlike the present study, several of these studies failed to consider various factors in their analyses that could be of interest in understanding these effects. Such factors include ERP latency, player position (i.e. a factor that is effectively an estimate of susceptibility to varying magnitudes and frequencies of impacts), and the amount of time spent "in play" during games. Brooks (2016) began to address some of these issues in his dissertation. He utilized quantitative measurements of impacts via a GForceTracker in conjunction with electrophysiological testing to understand changes in P3b amplitude in a sample of collegiate football players using a two-stimulus visual oddball paradigm. When investigating varying positions/skills it was found that small skilled and big skilled players showed an attenuated P3b at mid- and post-season as compared to baseline, whereas big unskilled players did not. They also found that at each skill level players with the most hits demonstrated a decreased P3b amplitude compared to those with the least hits. These results in conjunction with the present studies allow us to begin to disentangle susceptibility to cognitive alterations in high contact sports.

A large body of research has demonstrated that cumulative head impacts (and body impacts resulting in trauma to the head) can have lasting effects. Retired football players with a history of recurrent concussions are more likely to be clinically diagnosed with mild cognitive impairment or depression and have self-reported memory impairments (Guskiewicz et al., 2005; Guskiewicz et al., 2007). Studies also suggest a dose-response relationship between history of head trauma and late-life cognitive decline (Guskiewicz et al., 2005; Guskiewicz et al., 2007). These findings have been further validated by studies of electrophysiology. In studies comparing retired football and/or hockey players to their healthy counterparts it was discovered that the P3a was attenuated (De Beaumont et al., 2009; Ruiter et al., 2019) and delayed (De Beaumont et al., 2009) as was the P3b. Ruiter et al. (2019) also demonstrated an attenuated MMN in the retired athletes, suggesting poor automatic attentive processing due to a history of repeated head trauma. The combined results of these neuropsychological and neurophysiological evaluations offer strong support for the long-term consequences of repeated head trauma.

One of the most life-altering implications of these findings regarding the long-term consequences of concussions and subconcussive impacts is a disease called Chronic Traumatic Encephalopathy (CTE). CTE is a neurodegenerative tauopathy that has been linked to a history of repeated head trauma often associated with participation in contact sports such as football (Omalu et al., 2005; McKee et al., 2009; Baugh et al., 2012). A study examining post-mortem brain autopsies in six retired professional football players with a history of multiple concussions and clear neurocognitive decline before death found that only three cases had CTE (Hazrati et al., 2013). Thus, the researchers concluded that not all athletes with extensive concussion histories and football experience present with CTE. The findings of this study, however, hint that there might be other factors at play in considering susceptibility to CTE. In a more recent study involving the brains of over 200 deceased former football players (ranging from high school level to professional), Mez et al. (2017) found that an overwhelming 87% were diagnosed with CTE based on their neuropathology. Furthermore, most higher-level players had severe CTE pathologies, whereas all high school level players had mild CTE pathologies. Together these results suggest that although not all football players will ultimately develop CTE, perhaps it is not merely concussion history, but rather the mere exposure to repeated head and body impacts in football that predict the development of CTE. In a review of CTE in athletes it was found that the football players whose autopsies found pathologies consistent with CTE had all played similar positions, namely lineman and linebacker (McKee et al., 2009). Considering these positions are most likely to sustain a high frequency of hits (Crisco et al., 2010; Crisco et al., 2011; Funk et al., 2012), these combined results offer support for the significance of repetitive head impacts in understanding long-term implications of involvement in contact sports.

5. Conclusion

Given the potential long-term effects of repeated head and body impacts resulting in head trauma, there is a growing concern for athletes involved in high contact sports – sports in which a high frequency, and often high severity, of impacts is inevitable. A great deal of emphasis has been put on concussions as they are acutely clinically relevant to an individual's health, however more recently the focus has shifted to include subconcussive impacts as well. Numerous studies have suggested that it is not merely a history of concussion, but rather a history of cumulative head trauma that results in the most dire long-term outcomes. The present study offers support for the hypothesis that repeated subconcussive impacts can have significant effects on neurophysiological markers of cognitive health, even over the course of one football season. It also introduces additional variables to be considered in experiments of this kind (i.e. playing time and player position), and hints at the complexity of this line of research largely due to the variability in each athlete's experiences on the field. Future work should aim to further disentangle factors affecting susceptibility to both the acute and chronic effects of sports-related head trauma, and to utilize a known quantification of these impacts (i.e. accelerometers) in conjunction with ERPs to develop a more encompassing understanding of these issues.

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Appendices

Appendix A: Participant Screening Form

SCREENING FORM

Study # ___________ Participant code: __________ Date of birth: _____________ Test date: ___________

Handedness: □ Right □ Left □ Ambidextrous Sex: □ Male □ Female

Highest level of education: ____

Languages in order of fluency: 1. ______________________________ 2.________________________________

3. _________________________________ 4. _________________________________

If English is not your first language: How old were you when you learned English? ______________________________

If you were not born in Canada: How old were you when you moved to Canada? _________________________________

History of substance abuse: ____

Is your hearing and vision normal? □ Yes □ No

If not, please describe: ____

Have you ever had any perceptual (colour blindness) learning or language problems? □ Yes □ No

If yes, please describe (age, length, recovery): ____

Have you ever had any neurological, psychological or psychiatric problems? □ Yes □ No

If yes, please describe (age, length, recovery):____

Have you ever had a head injury, seizures, coordination problems or major surgeries? □ Yes □ No

If yes, please describe (age, length, recovery):____

Have you ever lost consciousness, had any fainting spells, paralysis or dizziness? □ Yes □ No

If yes, when and for how long? ____

Are you presently taking any medication? □ Yes □ No

If yes, which one(s)?____

Have you recently taken any medication? □ Yes □ No

If yes, which one(s), and when?____

Do you consume the following?

		How often?
Alcohol	□ Yes □ No	
Cigarettes	□ Yes □ No	
Drugs	□ Yes □ No	

How many hours did you sleep last night? _____________

How alert do you feel right now? (not very) 1 2 3 4 5 (very alert)

Appendix B: Edinburgh Handedness Inventory

Edinburgh Handedness Inventory[1]

Please indicate with a check (✓) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two checks (✓✓).

If you are indifferent, put one check in each column (✓ | ✓).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total checks:	LH =	RH =
Cumulative Total	CT = LH + RH =	
Difference	D = RH – LH =	
Result	R = (D / CT) × 100 =	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)		

[1] Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsycholodgia*, *9*, 97-113.

Appendix C: Post Concussion Symptom Scale

Name: ____________________ Age/DOB: _____________ Date of Injury:___________

Post Concussion Symptom Scale

No symptoms"0"-------Moderate "3"---------Severe"6"

Time after Concussion

SYMPTOMS	Days/Hrs ________	Days/Hrs ________	Days/Hrs ________
Headache	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Nausea	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Vomiting	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Balance problems	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Dizziness	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Fatigue	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Trouble falling to sleep	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Excessive sleep	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Loss of sleep	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Drowsiness	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Light sensitivity	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Noise sensitivity	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Irritability	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Sadness	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Nervousness	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
More emotional	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Numbness	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Feeling "slow"	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Feeling "foggy"	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Difficulty concentrating	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Difficulty remembering	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Visual problems	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
TOTAL SCORE	_____	_____	_____

Use of the Post-Concussion Symptom Scale: The athlete should fill out the form, on his or her own, in order to give a subjective value for each symptom. This form can be used with each encounter to track the athlete's progress towards the resolution of symptoms. Many athletes may have some of these reported symptoms at a baseline, such as concentration difficulties in the patient with attention-deficit disorder or sadness in an athlete with underlying depression, and must be taken into consideration when interpreting the score. Athletes do not have to be at a total score of zero to return to play if they already have had some symptoms prior to their concussion.

Appendix D: Beck Depression Inventory (II)

Beck's Depression Inventory

This depression inventory can be self-scored. The scoring scale is at the end of the questionnaire.

1.
- 0 I do not feel sad.
- 1 I feel sad
- 2 I am sad all the time and I can't snap out of it.
- 3 I am so sad and unhappy that I can't stand it.

2.
- 0 I am not particularly discouraged about the future.
- 1 I feel discouraged about the future.
- 2 I feel I have nothing to look forward to.
- 3 I feel the future is hopeless and that things cannot improve.

3.
- 0 I do not feel like a failure.
- 1 I feel I have failed more than the average person.
- 2 As I look back on my life, all I can see is a lot of failures.
- 3 I feel I am a complete failure as a person.

4.
- 0 I get as much satisfaction out of things as I used to.
- 1 I don't enjoy things the way I used to.
- 2 I don't get real satisfaction out of anything anymore.
- 3 I am dissatisfied or bored with everything.

5.
- 0 I don't feel particularly guilty
- 1 I feel guilty a good part of the time.
- 2 I feel quite guilty most of the time.
- 3 I feel guilty all of the time.

6.
- 0 I don't feel I am being punished.
- 1 I feel I may be punished.
- 2 I expect to be punished.
- 3 I feel I am being punished.

7.
- 0 I don't feel disappointed in myself.
- 1 I am disappointed in myself.
- 2 I am disgusted with myself.
- 3 I hate myself.

8.
- 0 I don't feel I am any worse than anybody else.
- 1 I am critical of myself for my weaknesses or mistakes.
- 2 I blame myself all the time for my faults.
- 3 I blame myself for everything bad that happens.

9.
- 0 I don't have any thoughts of killing myself.
- 1 I have thoughts of killing myself, but I would not carry them out.
- 2 I would like to kill myself.
- 3 I would kill myself if I had the chance.

10.
- 0 I don't cry any more than usual.
- 1 I cry more now than I used to.
- 2 I cry all the time now.
- 3 I used to be able to cry, but now I can't cry even though I want to.

11.
0 I am no more irritated by things than I ever was.
1 I am slightly more irritated now than usual.
2 I am quite annoyed or irritated a good deal of the time.
3 I feel irritated all the time.

12.
0 I have not lost interest in other people.
1 I am less interested in other people than I used to be.
2 I have lost most of my interest in other people.
3 I have lost all of my interest in other people.

13.
0 I make decisions about as well as I ever could.
1 I put off making decisions more than I used to.
2 I have greater difficulty in making decisions more than I used to.
3 I can't make decisions at all anymore.

14.
0 I don't feel that I look any worse than I used to.
1 I am worried that I am looking old or unattractive.
2 I feel there are permanent changes in my appearance that make me look unattractive
3 I believe that I look ugly.

15.
0 I can work about as well as before.
1 It takes an extra effort to get started at doing something.
2 I have to push myself very hard to do anything.
3 I can't do any work at all.

16.
0 I can sleep as well as usual.
1 I don't sleep as well as I used to.
2 I wake up 1-2 hours earlier than usual and find it hard to get back to sleep.
3 I wake up several hours earlier than I used to and cannot get back to sleep.

17.
0 I don't get more tired than usual.
1 I get tired more easily than I used to.
2 I get tired from doing almost anything.
3 I am too tired to do anything.

18.
0 My appetite is no worse than usual.
1 My appetite is not as good as it used to be.
2 My appetite is much worse now.
3 I have no appetite at all anymore.

19.
0 I haven't lost much weight, if any, lately.
1 I have lost more than five pounds.
2 I have lost more than ten pounds.
3 I have lost more than fifteen pounds.

20.

0	I am no more worried about my health than usual.
1	I am worried about physical problems like aches, pains, upset stomach, or constipation.
2	I am very worried about physical problems and it's hard to think of much else.
3	I am so worried about my physical problems that I cannot think of anything else.

21.

0	I have not noticed any recent change in my interest in sex.
1	I am less interested in sex than I used to be.
2	I have almost no interest in sex.
3	I have lost interest in sex completely.

INTERPRETING THE BECK DEPRESSION INVENTORY

Now that you have completed the questionnaire, add up the score for each of the twenty-one questions by counting the number to the right of each question you marked. The highest possible total for the whole test would be sixty-three. This would mean you circled number three on all twenty-one questions. Since the lowest possible score for each question is zero, the lowest possible score for the test would be zero. This would mean you circles zero on each question. You can evaluate your depression according to the Table below.

Total Score	Levels of Depression
1-10	These ups and downs are considered normal
11-16	Mild mood disturbance
17-20	Borderline clinical depression
21-30	Moderate depression
31-40	Severe depression
over 40	Extreme depression

Appendix E: SF-36 Health Survey

Your Health and Well-Being

This survey asks for your views about your health. This information will help keep track of how you feel and how well you are able to do your usual activities. *Thank you for completing this survey!*

For each of the following questions, please mark an ☒ in the one box that best describes your answer.

1. In general, would you say your health is:

Excellent	Very good	Good	Fair	Poor
☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

2. <u>Compared to one year ago</u>, how would you rate your health in general <u>now</u>?

Much better now than one year ago	Somewhat better now than one year ago	About the same as one year ago	Somewhat worse now than one year ago	Much worse now than one year ago
☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

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3. The following questions are about activities you might do during a typical day. Does <u>your health now limit you</u> in these activities? If so, how much?

	Yes, limited a lot	Yes, limited a little	No, not limited at all
a Vigorous activities, such as running, lifting heavy objects, participating in strenuous sports	☐ 1	☐ 2	☐ 3
b Moderate activities, such as moving a table, pushing a vacuum cleaner, bowling, or playing golf	☐ 1	☐ 2	☐ 3
c Lifting or carrying groceries	☐ 1	☐ 2	☐ 3
d Climbing several flights of stairs	☐ 1	☐ 2	☐ 3
e Climbing one flight of stairs	☐ 1	☐ 2	☐ 3
f Bending, kneeling, or stooping	☐ 1	☐ 2	☐ 3
g Walking more than a kilometre	☐ 1	☐ 2	☐ 3
h Walking several hundred metres	☐ 1	☐ 2	☐ 3
i Walking one hundred metres	☐ 1	☐ 2	☐ 3
j Bathing or dressing yourself	☐ 1	☐ 2	☐ 3

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4. During the past 4 weeks, how much of the time have you had any of the following problems with your work or other regular daily activities as a result of your physical health?

	All of the time	Most of the time	Some of the time	A little of the time	None of the time
a Cut down on the amount of time you spent on work or other activities	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
b Accomplished less than you would like	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
c Were limited in the kind of work or other activities	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
d Had difficulty performing the work or other activities (for example, it took extra effort)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

5. During the past 4 weeks, how much of the time have you had any of the following problems with your work or other regular daily activities as a result of any emotional problems (such as feeling depressed or anxious)?

	All of the time	Most of the time	Some of the time	A little of the time	None of the time
a Cut down on the amount of time you spent on work or other activities	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
b Accomplished less than you would like	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
c Did work or other activities less carefully than usual	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

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6. During the <u>past 4 weeks</u>, to what extent has your physical health or emotional problems interfered with your normal social activities with family, friends, neighbours, or groups?

Not at all	Slightly	Moderately	Quite a bit	Extremely
☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

7. How much <u>bodily</u> pain have you had during the <u>past 4 weeks</u>?

None	Very mild	Mild	Moderate	Severe	Very severe
☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6

8. During the <u>past 4 weeks</u>, how much did <u>pain</u> interfere with your normal work (including both work outside the home and housework)?

Not at all	A little bit	Moderately	Quite a bit	Extremely
☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

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9. These questions are about how you feel and how things have been with you <u>during the past 4 weeks</u>. For each question, please give the one answer that comes closest to the way you have been feeling. How much of the time during the <u>past 4 weeks</u>…

	All of the time	Most of the time	Some of the time	A little of the time	None of the time
a Did you feel full of life?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
b Have you been very nervous?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
c Have you felt so down in the dumps that nothing could cheer you up?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
d Have you felt calm and peaceful?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
e Did you have a lot of energy?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
f Have you felt downhearted and depressed?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
g Did you feel worn out?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
h Have you been happy?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
i Did you feel tired?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

10. During the <u>past 4 weeks</u>, how much of the time has your <u>physical health or emotional problems</u> interfered with your social activities (like visiting with friends, relatives, etc.)?

All of the time	Most of the time	Some of the time	A little of the time	None of the time
☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

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11. How TRUE or FALSE is <u>each</u> of the following statements for you?

	Definitely true	Mostly true	Don't know	Mostly false	Definitely false
a I seem to get sick a little easier than other people	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
b I am as healthy as anybody I know	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
c I expect my health to get worse	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
d My health is excellent	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

Thank you for completing these questions!

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Appendix F: Online Participant Survey – Experiment 1

LMB Concussion Study Injury Information

There are 14 questions in this survey.

Participant

For researcher/assistant(s) use.

Are you a varsity athlete or control? *

Choose one of the following answers
Please choose **only one** of the following:

- Athlete
- Control
- Other

If unsure, please ask researcher/assistant(s).

What is the purpose of today's testing?

*

Choose one of the following answers
Please choose **only one** of the following:

- ◯ Baseline
- ◯ End of Season
- ◯ Injury 1
- ◯ Injury 2
- ◯ Injury 3
- ◯ Injury 4
- ◯ Injury 5
- ◯ Injury 6
- ◯ Injury 7
- ◯ Injury 8
- ◯ Injury 9
- ◯ Injury 10+

Make a comment on your choice here:

If participant has been tested over 10 times for this study within this season, please indicate the number in the comment box.

Concussion Screening

How many concussions have you sustained? If you have sustained more than 6, please indicate how many in the "other" section. *

Choose one of the following answers

Please choose **only one** of the following:

- ◯ 0
- ◯ 1
- ◯ 2
- ◯ 3
- ◯ 4
- ◯ 5
- ◯ 6
- ◯ Other

Concussed

When was your most recent concussion? Be specific to month and year- exact date can be approximate.

If you cannot remember the date your injury occurred, but have an approximate idea, please go by the following:

1st= beginning of month; 15th= middle of month; 30th= end of month

*

Only answer this question if the following conditions are met:
Answer was '1' *or* '2' *or* '3' *or* '4' *or* '5' *or* '6' *or* 'Other' at question '3 [NOCs]' (How many concussions have you sustained? If you have sustained more than 6, please indicate how many in the "other" section.)

Please enter a date:

How did you acquire your most recent concussion? *

Only answer this question if the following conditions are met:
Answer was '4' *or* '1' *or* '3' *or* '2' *or* '5' *or* '6' *or* 'Other' at question '3 [NOCs]' (How many concussions have you sustained? If you have sustained more than 6, please indicate how many in the "other" section.)

❗ Choose one of the following answers
Please choose **only one** of the following:

- ◯ Sports
- ◯ Motor Vehicle Collision
- ◯ Assault
- ◯ Prefer not to answer
- ◯ Other

If other, please indicate how you acquired your most recent concussion.

Sports Injury

Please identify which sport you were playing at the time of your most recent concussion. *

Only answer this question if the following conditions are met:
Answer was 'Sports' at question '5 [Cause]' (How did you acquire your most recent concussion?)

Choose one of the following answers
Please choose **only one** of the following:

- Football
- Rugby
- Hockey
- Soccer
- Basketball
- Baseball/Softball
- Ski/Snowboarding
- Skating
- Bicycling
- Horseback Riding
- Skateboarding/Rollerblading
- Other

If Other, please specify which sport/activity you were doing at the time of your most recent concussion.

Which position were you playing at time of your most recent concussion?

If not applicable please write "N/A".

*

Only answer this question if the following conditions are met:
Answer was 'Sports' at question '5 [Cause]' (How did you acquire your most recent concussion?)

Please write your answer here:

MVC Injury

Please indicate the speed at which the motor vehicle collision occurred. *

Only answer this question if the following conditions are met:
Answer was 'Motor Vehicle Collision' at question '5 [Cause]' (How did you acquire your most recent concussion?)

Choose one of the following answers
Please choose **only one** of the following:

- Low speed <40 km/hr
- Moderate speed 40-80 km/hr
- High speed >80 km/hr

Please indicate your position at time of the accident. *

Only answer this question if the following conditions are met:
Answer was 'Motor Vehicle Collision' at question '5 [Cause]' (How did you acquire your most recent concussion?)

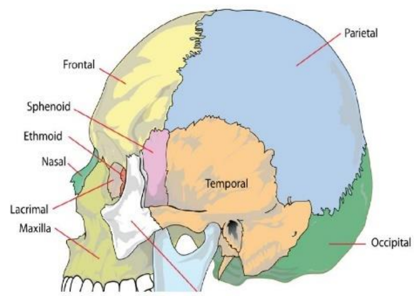
❶ Choose one of the following answers
Please choose **only one** of the following:

- ◯ Driver of car
- ◯ Passenger in car
- ◯ Pedestrian
- ◯ Cyclist
- ◯ Other

If Other, please indicate.

Injury Acquisition

If you were hit on the head, or your head hit an object (e.g. dashboard of car), please specify where the PRIMARY contact occurred during your most recent concussion. Note: indirect force is an option.



*

Only answer this question if the following conditions are met:
Answer was 'Prefer not to answer' *or* 'Sports' *or* 'Motor Vehicle Collision' *or* 'Assault' *or* 'Other' at question '5 [Cause]' (How did you acquire your most recent concussion?) *and* Answer was '1' *or* '2' *or* '3' *or* '4' *or* '5' *or* '6' *or* 'Other' at question '3 [NOCs]' (How many concussions have you sustained? If you have sustained more than 6, please indicate how many in the "other" section.)

❗ Choose one of the following answers
Please choose **only one** of the following:

- ◯ Frontal (forehead)
- ◯ Occipital (back)
- ◯ Left Temporal (close to ear)
- ◯ Right Temporal (close to ear)
- ◯ Left Parietal (top)
- ◯ Right Parietal (top)
- ◯ Left Jaw
- ◯ Right Jaw
- ◯ Neck
- ◯ Face
- ◯ Other body part
- ◯ Indirect Force

◯ Other

If Other, please indicate.

When you sustained your most recent concussion, were you rendered unconscious? If yes, please indicate how long in the comment box. *

Only answer this question if the following conditions are met:
Answer was 'Occipital (back) ' *or* 'Frontal (forehead)' *or* 'Left Temporal (close to ear)' *or* 'Right Temporal (close to ear)' *or* 'Left Parietal (top)' *or* 'Right Parietal (top)' *or* 'Left Jaw' *or* 'Right Jaw' *or* 'Neck' *or* 'Face' *or* 'Other body part' *or* 'Indirect Force' *or* 'Other' at question '10 [HitLoc]' (If you were hit on the head, or your head hit an object (e.g. dashboard of car), please specify where the PRIMARY contact occurred during your most recent concussion. Note: indirect force is an option.) *and* Answer was '1' *or* '2' *or* '3' *or* '4' *or* '5' *or* '6' *or* 'Other' at question '3 [NOCs]' (How many concussions have you sustained? If you have sustained more than 6, please indicate how many in the "other" section.)

❶ Choose one of the following answers
Please choose **only one** of the following:

◯ Yes

◯ No

Make a comment on your choice here:

Was your most recent concussion formally diagnosed by a health care professional/provider? If yes, in the comment box please provide the following:

The **name** of the health care professional/provider

When you saw them

How long after your concussion you saw them.

*

Only answer this question if the following conditions are met:
Answer was '1' *or* '2' *or* '3' *or* '4' *or* '5' *or* '6' *or* 'Other' at question '3 [NOCs]' (How many concussions have you sustained? If you have sustained more than 6, please indicate how many in the "other" section.)

❶ Choose one of the following answers
Please choose **only one** of the following:

◯ Yes

◯ No

Make a comment on your choice here:

PRIOR to your most recent concussion, did you experience any of the following symptoms? (0= no, 3=moderate, 6=severe)

*

Only answer this question if the following conditions are met:
Answer was '1' *or* '2' *or* '3' *or* '4' *or* '5' *or* '6' *or* 'Other' at question '3 [NOCs]' (How many concussions have you sustained? If you have sustained more than 6, please indicate how many in the "other" section.)

Please choose the appropriate response for each item:

	0	1	2	3	4	5	6
Headache	○	○	○	○	○	○	○
Nausea	○	○	○	○	○	○	○
Vomiting	○	○	○	○	○	○	○
Balance Problems	○	○	○	○	○	○	○
Dizziness	○	○	○	○	○	○	○
Fatigue	○	○	○	○	○	○	○
Trouble Falling Asleep	○	○	○	○	○	○	○
Excessive Sleep	○	○	○	○	○	○	○
Loss of Sleep	○	○	○	○	○	○	○
Drowsiness	○	○	○	○	○	○	○
Light Sensitivity	○	○	○	○	○	○	○
Noise Sensitivity	○	○	○	○	○	○	○
Irritability	○	○	○	○	○	○	○

	0	1	2	3	4	5	6
Sadness	◯	◯	◯	◯	◯	◯	◯
Nervousness	◯	◯	◯	◯	◯	◯	◯
More emotional	◯	◯	◯	◯	◯	◯	◯
Numbness	◯	◯	◯	◯	◯	◯	◯
Feeling "Slow"	◯	◯	◯	◯	◯	◯	◯
Feeling "Foggy"	◯	◯	◯	◯	◯	◯	◯
Difficulty Concentrating	◯	◯	◯	◯	◯	◯	◯
Difficulty Remembering	◯	◯	◯	◯	◯	◯	◯
Visual Problems	◯	◯	◯	◯	◯	◯	◯

Concussion History

Please indicate:

- **when** you sustained previous concussion(s),

- **brief description** of what happened,

-if you were **rendered unconscious,**

-if they were diagnosed by a health care professional/provider and

-the **name of the health care professional/provider** that provided the diagnosis.

<u>Example</u>: Jan 2015, hit to back of head during hockey game, unconscious for 30 minutes, diagosed by family doctor, Dr. Example.

Mar 2016, whiplash and concussion from rear-end collision at low speed, no loss of consciousness, did not see a health care professional/provider.

Only answer this question if the following conditions are met:
Answer was '2' *or* '3' *or* '4' *or* '5' *or* '6' *or* 'Other' at question '3 [NOCs]' (How many concussions have you sustained? If you have sustained more than 6, please indicate how many in the "other" section.)

Please write your answer here:

If you cannot remember exact details please provide as many as possible.

Thank you for taking this survey. Your answers are a valuable part of this research.

08-31-2019 – 16:10

Submit your survey.

Thank you for completing this survey.

Appendix G: Online Participant Survey – Experiment 2

LMB Varsity Survey UPDATED (2019-2020)

There are 60 questions in this survey.

Researcher Input

Participant code: *

Please write your answer here:

What is the purpose of today's testing? *

Choose one of the following answers

Please choose **only one** of the following:

- Baseline
- Concussion 1
- Concussion 2
- Concussion 3
- Concussion 4
- Concussion 5
- Concussion 6+
- Post-season

Do you play a contact or non-contact sport? *

❶ Choose one of the following answers
Please choose **only one** of the following:

- ◯ Contact
- ◯ Non-contact

Test date: *

❶ Answer must be greater or equal to 09.08.2019
Please enter a date:

Screening Form

First Name: *

Please write your answer here:

Last Name: *

Please write your answer here:

Sex: *

Choose one of the following answers
Please choose **only one** of the following:

- ◯ Male
- ◯ Female
- ◯ Other

Highest level of education: *

Choose one of the following answers
Please choose **only one** of the following:

- ◯ No Formal Education
- ◯ High School
- ◯ College
- ◯ University
- ◯ Some College/University
- ◯ Vocational Training
- ◯ Masters
- ◯ Doctorate / PHD
- ◯ Other

Handedness: *

❶ Choose one of the following answers
Please choose **only one** of the following:

- ◯ Right
- ◯ Left
- ◯ Ambidextrous

Date of birth: *

❶ Please complete all parts of the date.
❶ Answer must be less or equal to 31.12.2002
Please enter a date:

Language(s) in order of fluency:

Is English your native language? *

❶ Choose one of the following answers
Please choose **only one** of the following:

- ◯ Yes
- ◯ No

How old were you when you first learned English? *

Only answer this question if the following conditions are met:
Answer was 'No' at question '12 [L1]' (Is English your native language?)

❶ Only numbers may be entered in this field.
Please write your answer here:

Please enter a numerical value (e.g. if you were 5 years old, write "5").

Were you born in Canada? *

❶ Choose one of the following answers
Please choose **only one** of the following:

- Yes
- No

How old were you when you moved to Canada? *

Only answer this question if the following conditions are met:
Answer was 'No' at question '14 [Canada]' (Were you born in Canada?)

❶ Only numbers may be entered in this field.
Please write your answer here:

Please enter a numerical value (e.g. if you were 5 years old, write "5").

Is your vision normal or corrected-to-normal? *

Choose one of the following answers
Please choose **only one** of the following:

- ◯ Yes
- ◯ No

Please describe any vision issues. *

Only answer this question if the following conditions are met:
Answer was 'No' at question '16 [Vision]' (Is your vision normal or corrected-to-normal?)

Please write your answer here:

Is your hearing normal or corrected-to-normal? *

Choose one of the following answers
Please choose **only one** of the following:

- ◯ Yes
- ◯ No

Please describe any hearing issues. *

Only answer this question if the following conditions are met:
Answer was 'No' at question '18 [Hearing]' (Is your hearing normal or corrected-to-normal?)

Please write your answer here:

Have you ever had any neurological, psychological, or psychiatric problems? *

Choose one of the following answers
Please choose **only one** of the following:

- Yes
- No

Please describe any neurological, psychological, or psychiatric problems. *

Only answer this question if the following conditions are met:
Answer was 'Yes' at question '20 [NPPProblems]' (Have you ever had any neurological, psychological, or psychiatric problems?)

Please write your answer here:

Describe age, length, and recovery

Have you ever had any perceptual (such as colour blindness), learning, or language problems?

*

Choose one of the following answers
Please choose **only one** of the following:

- Yes
- No

Please describe any perceptual (such as colour blindness), learning, or language problems. *

Only answer this question if the following conditions are met:
Answer was 'Yes' at question '22 [PLLProblems]' (Have you ever had any perceptual (such as colour blindness), learning, or language problems?)

Please write your answer here:

Describe age, length, and recovery

Are you presently taking any medication? *

Choose one of the following answers
Please choose **only one** of the following:

- ◯ Yes
- ◯ No

Which medications are you presently taking? *

Only answer this question if the following conditions are met:
Answer was 'Yes' at question '24 [Medications]' (Are you presently taking any medication?)

Please write your answer here:

Have you taken any medications in the last 24 hours? *

Choose one of the following answers
Please choose **only one** of the following:

- Yes
- No

Which medications have you taken in the last 24 hours? *

Only answer this question if the following conditions are met:
Answer was 'Yes' at question '26 [MedicationCont]' (Have you taken any medications in the last 24 hours?)

Please write your answer here:

How often do you consume the following? *

Please choose the appropriate response for each item:

	A few times a week	About once a week	At least once a month	A few times a year	Never
Alcohol	◯	◯	◯	◯	◯
Cigarettes/vapes	◯	◯	◯	◯	◯
Cannabis	◯	◯	◯	◯	◯
Other recreational drugs	◯	◯	◯	◯	◯

Have you ever lost consciousness, had any fainting spells, paralysis, or dizziness?

*

❗ Choose one of the following answers

Please choose **only one** of the following:

◯ Yes

◯ No

Please describe the time(s) you lost consciousness, had any fainting spells, paralysis, or dizziness? *

Only answer this question if the following conditions are met:
Answer was 'Yes' at question '29 [ConsciousnessHistory]' (Have you ever lost consciousness, had any fainting spells, paralysis, or dizziness?)

Please write your answer here:

Describe age, length, and recovery

How alert do you feel right now? (1 = not very, 5 = very alert) *

Please choose the appropriate response for each item:

	1	2	3	4	5
Level of alertness	○	○	○	○	○

How many hours did you sleep last night? *

Only numbers may be entered in this field.
Please write your answer here:

Please enter a numerical value.

Did you sleep more, less, or about an equal number of hours as compared to your average amount? *

Choose one of the following answers

Please choose **only one** of the following:

- More
- Less
- Average

How well have you been sleeping for the past week? (1 = not very, 5 = very well) *

Please choose the appropriate response for each item:

	1	2	3	4	5
Sleep quality	◯	◯	◯	◯	◯

Your Health and Well-Being (SF-36)

This survey asks for your views about your health. This information will help keep track of how you feel about how well you are able to do your usual activities.

In general, would you say your health is: *

Please choose the appropriate response for each item:

	Excellent	Very good	Good	Fair	Poor
	◯	◯	◯	◯	◯

<u>Compared to one year ago</u>, how would you rate your health in general now? *

Please choose the appropriate response for each item:

	Much better now than one year ago	**Somewhat better now than one year ago**	**About the same now as one year ago**	**Somewhat worse now than one year ago**	**Much worse now than one year ago**
	○	○	○	○	○

The following questions are about activities you might do during a typical day. Does your health now limit you in these activities? If so, how much? *

Please choose the appropriate response for each item:

	Yes, limited a lot	Yes, limited a little	No, not limited at all
Vigorous activities, such as running, lifting heavy objects, participating in strenuous sports	○	○	○
Moderate activities, such as moving a table, pushing a vacuum cleaner, bowling, or playing golf	○	○	○
Lifting or carrying groceries	○	○	○
Climbing several flights of stairs	○	○	○
Climbing one flight of stairs	○	○	○
Bending, kneeling, or stooping	○	○	○
Walking more than a mile	○	○	○
Walking several blocks	○	○	○
Walking one block	○	○	○
Bathing or dressing yourself	○	○	○

During the past 4 weeks, have you had any of the following problems with your work or other regular daily activities as a result of your physical health? *

Please choose the appropriate response for each item:

	Yes	No
Cut down on the amount of time you spent on work or other activities	○	○
Accomplished less than you would like	○	○
Were limited in the kind of work or other activities	○	○
Had difficulty performing the work or other activities (for example, it took extra effort)	○	○

During the past 4 weeks, have you had any of the following problems with your work or other regular daily activities as a result of any emotional problems (such as feeling depressed or anxious)? *

Please choose the appropriate response for each item:

	Yes	No
Cut down on the amount of time you spent on work or other activities	○	○
Accomplished less than you would like	○	○
Did work or other activities less carefully than usual	○	○

During the past 4 weeks, to what extent has your physical health or emotional problems interfered with your normal social activities with family, friends, neighbors, or groups? *

Please choose the appropriate response for each item:

	Not at all	Slightly	Moderately	Quite a bit	Extremely
Answer:	○	○	○	○	○

How much bodily pain have you had during the past 4 weeks? *

Please choose the appropriate response for each item:

	None	Very mild	Mild	Moderate	Severe	Very severe
Answer:	◯	◯	◯	◯	◯	◯

During the past 4 weeks, how much did pain interfere with your normal work (including both work outside the home and housework)? *

Please choose the appropriate response for each item:

	Not at all	A little bit	Moderately	Quite a bit	Extremely
Answer:	◯	◯	◯	◯	◯

These questions are about how you feel and how things have been with you during the past 4 weeks. For each question, please give the one answer that comes closest to the way you have been feeling. How much of the time during the past 4 weeks... *

Please choose the appropriate response for each item:

	All of the time	Most of the time	Some of the time	A little of the time	None of the time
Did you feel full of pep?	○	○	○	○	○
Have you been a very nervous person?	○	○	○	○	○
Have you felt so down in the dumps that nothing could cheer you up?	○	○	○	○	○
Have you felt calm and peaceful?	○	○	○	○	○
Did you have a lot of energy?	○	○	○	○	○
Have you felt downhearted and blue?	○	○	○	○	○
Did you feel worn out?	○	○	○	○	○
Have you been a happy person?	○	○	○	○	○
Did you feel tired?	○	○	○	○	○

During the past 4 weeks, how much of the time has your physical health or emotional problems interfered with your social activities (like visiting with friends, relatives, etc.)? *

Please choose the appropriate response for each item:

	All of the time	Most of the time	Some of the time	A little of the time	None of the time
Answer:	◯	◯	◯	◯	◯

How TRUE or FALSE is each of the following statements for you? *

Please choose the appropriate response for each item:

	Definitely true	Mostly true	Don't know	Mostly false	Definitely false
I seem to get sick a little easier than other people	◯	◯	◯	◯	◯
I am as healthy as anybody I know	◯	◯	◯	◯	◯
I expect my health to get worse	◯	◯	◯	◯	◯
My health is excellent	◯	◯	◯	◯	◯

Perceived Stress Scale (PSS)

The questions in this scale ask you about your feelings and thoughts during <u>the last month</u>. In each case please indicate your response representing <u>how often</u> you felt or thought a certain way.

In the last month... *

Please choose the appropriate response for each item:

	Never	Almost never	Sometimes	Fairly often	Very often
How often have you been upset because of something that happened unexpectedly?	○	○	○	○	○
How often have you felt that you were unable to control the important things in your life?	○	○	○	○	○
How often have you felt nervous and "stressed"?	○	○	○	○	○
How often have you felt confident about your ability to handle your personal problems?	○	○	○	○	○
How often have you felt that things were going your way?	○	○	○	○	○
How often have you found that you could not cope with all the things that you had to do?	○	○	○	○	○
How often have you been able to control irritations in your life?	○	○	○	○	○
How often have you felt that you were on top of things?	○	○	○	○	○

	Never	Almost never	Sometimes	Fairly often	Very often
How often have you been angered because of things that were outside your control?	◯	◯	◯	◯	◯
How often have you felt difficulties were piling up so high that you could not overcome them?	◯	◯	◯	◯	◯

Concussion Screening

What is the **total** number of concussions you have sustained to date? If you have sustained more than 6, please indicate how many in the "other" section. *

❶ Choose one of the following answers

Please choose **only one** of the following:

◯ 0
◯ 1
◯ 2
◯ 3
◯ 4
◯ 5
◯ 6
◯ Other

Of the concussions you have sustained, how many were **sports-related**? *

Only answer this question if the following conditions are met:
Answer was NOT '0' at question '47 [NOCs]' (What is the total number of concussions you have sustained to date? If you have sustained more than 6, please indicate how many in the "other" section.)

Choose one of the following answers
Please choose **only one** of the following:

- ◯ 0
- ◯ 1
- ◯ 2
- ◯ 3
- ◯ 4
- ◯ 5
- ◯ 6
- ◯ Other

When did you sustain your most recent concussion? *

Only answer this question if the following conditions are met:
Answer was NOT '0' at question '47 [NOCs]' (What is the total number of concussions you have sustained to date? If you have sustained more than 6, please indicate how many in the "other" section.) *and* Answer was 'Concussion 2' *or* 'Concussion 3' *or* 'Concussion 4' *or* 'Concussion 5' *or* 'Concussion 6+' *or* 'Concussion 1' at question '2 [Testing]' (What is the purpose of today's testing?)

Answer must be greater or equal to 09.08.2019
Please enter a date:

If you cannot remember the exact date please provide an estimate.

If you were hit on the head, or your head hit an object (e.g. dashboard of a car), please specify where the PRIMARY contact occurred during your most recent concussion. Note: indirect force is an option.

*

Only answer this question if the following conditions are met:
Answer was NOT '0' at question '47 [NOCs]' (What is the total number of concussions you have sustained to date? If you have sustained more than 6, please indicate how many in the "other" section.) *and* Answer was 'Concussion 1' *or* 'Concussion 2' *or* 'Concussion 3' *or* 'Concussion 4' *or* 'Concussion 5' *or* 'Concussion 6+' at question '2 [Testing]' (What is the purpose of today's testing?)

❶ Choose one of the following answers
Please choose **only one** of the following:

- ◯ Frontal (forehead)
- ◯ Occipital (back
- ◯ Left Temporal (close to ear)
- ◯ Right Temporal (close to ear)
- ◯ Left Parietal (top)
- ◯ Right Parietal (top)
- ◯ Left Jaw
- ◯ Right Jaw
- ◯ Neck
- ◯ Face
- ◯ Other body part
- ◯ Indirect force
- ◯ Other ______

If other, please indicate.

When you sustained your most recent concussion, did you lose consciousness? *

Only answer this question if the following conditions are met:
Answer was NOT '0' at question '47 [NOCs]' (What is the total number of concussions you have sustained to date? If you have sustained more than 6, please indicate how many in the "other" section.) *and* Answer was 'Concussion 1' *or* 'Concussion 2' *or* 'Concussion 3' *or* 'Concussion 4' *or* 'Concussion 5' *or* 'Concussion 6+' at question '2 [Testing]' (What is the purpose of today's testing?)

❶ Choose one of the following answers
Please choose **only one** of the following:

◯ Yes
◯ No

Was your most recent concussion diagnosed by a health care professional/provider? *

Only answer this question if the following conditions are met:
Answer was NOT '0' at question '47 [NOCs]' (What is the total number of concussions you have sustained to date? If you have sustained more than 6, please indicate how many in the "other" section.) *and* Answer was 'Concussion 1' *or* 'Concussion 2' *or* 'Concussion 3' *or* 'Concussion 4' *or* 'Concussion 5' *or* 'Concussion 6+' at question '2 [Testing]' (What is the purpose of today's testing?)

❶ Choose one of the following answers
Please choose **only one** of the following:

◯ Yes
◯ No

If you are currently experiencing any of the following symptoms, please indicate the severity of each. (0 = no, 3 = moderate, 6 = severe) *

Please choose the appropriate response for each item:

	0	1	2	3	4	5	6
Headache	○	○	○	○	○	○	○
Nausea	○	○	○	○	○	○	○
Vomiting	○	○	○	○	○	○	○
Balance Problems	○	○	○	○	○	○	○
Dizziness	○	○	○	○	○	○	○
Fatigue	○	○	○	○	○	○	○
Trouble Falling Asleep	○	○	○	○	○	○	○
Excessive Sleep	○	○	○	○	○	○	○
Loss of Sleep	○	○	○	○	○	○	○
Drowsiness	○	○	○	○	○	○	○
Light Sensitivity	○	○	○	○	○	○	○
Noise Sensitivity	○	○	○	○	○	○	○
Irritability	○	○	○	○	○	○	○
Sadness	○	○	○	○	○	○	○

	0	1	2	3	4	5	6
Nervousness	◯	◯	◯	◯	◯	◯	◯
More emotional	◯	◯	◯	◯	◯	◯	◯
Numbness	◯	◯	◯	◯	◯	◯	◯
Feeling "Slow"	◯	◯	◯	◯	◯	◯	◯
Feeling "Foggy"	◯	◯	◯	◯	◯	◯	◯
Difficulty Concentrating	◯	◯	◯	◯	◯	◯	◯
Difficulty Remembering	◯	◯	◯	◯	◯	◯	◯
Visual Problems	◯	◯	◯	◯	◯	◯	◯

Sports Injury

What is your primary sport? If you are on a varsity sports team, please select the corresponding sport.

❶ Choose one of the following answers

Please choose **only one** of the following:

- ◯ Football
- ◯ Rugby
- ◯ Hockey
- ◯ Soccer
- ◯ Basketball
- ◯ Baseball/Softball
- ◯ Ski/Snowboarding
- ◯ Skating
- ◯ Bicycling
- ◯ Horseback Riding
- ◯ Skateboarding/Rollerblading
- ◯ Running
- ◯ Swimming
- ◯ Squash
- ◯ Badminton
- ◯ Other ____________

What position do you play? *

Only answer this question if the following conditions are met:
Answer was 'Football' at question '54 [SportPlay]' (What is your primary sport? If you are on a varsity sports team, please select the corresponding sport.)

❶ Choose one of the following answers
Please choose **only one** of the following:

- ◯ Quarterback
- ◯ Wide receiver
- ◯ Defensive back
- ◯ Running back
- ◯ Linebacker
- ◯ Offensive lineman
- ◯ Defensive lineman
- ◯ Special teams
- ◯ Other ________

How many years have you spent playing your primary sport? *

Choose one of the following answers
Please choose **only one** of the following:

- Less than 1 year
- 1 - 2 years
- 2 - 4 years
- 4 - 6 years
- 6 - 8 years
- 8 - 10 years
- 10 + years
- N/A

How many years in total have you spent playing contact sports? (e.g. basketball, soccer, rugby etc.) *

Choose one of the following answers
Please choose **only one** of the following:

- None
- Less than 1 year
- 1 - 2 years
- 2 - 4 years
- 4 - 6 years
- 6 - 8 years
- 8 - 10 years
- 10 + years

Were you playing your primary sport at the time of your most recent concussion? *

Only answer this question if the following conditions are met:
Answer was NOT '0' at question '47 [NOCs]' (What is the total number of concussions you have sustained to date? If you have sustained more than 6, please indicate how many in the "other" section.) *and* Answer was 'Concussion 3' *or* 'Concussion 4' *or* 'Concussion 5' *or* 'Concussion 6+' *or* 'Concussion 1' *or* 'Concussion 2' at question '2 [Testing]' (What is the purpose of today's testing?)

Choose one of the following answers
Please choose **only one** of the following:

- ◯ Yes
- ◯ No

Please specify which sport/activity you were doing at the time of your most recent concussion. *

Only answer this question if the following conditions are met:
Answer was NOT '0' at question '47 [NOCs]' (What is the total number of concussions you have sustained to date? If you have sustained more than 6, please indicate how many in the "other" section.) *and* Answer was 'No' at question '58 [SportConc]' (Were you playing your primary sport at the time of your most recent concussion?)

Please write your answer here:

What are the total minutes of play you have had this season? *

Only answer this question if the following conditions are met:
Answer was 'Contact' at question '3 [Subject1]' (Do you play a contact or non-contact sport?) *and* Answer was NOT 'Baseline' at question '2 [Testing]' (What is the purpose of today's testing?)

❶ Only numbers may be entered in this field.
Please write your answer here:

Thank you for taking this survey. Your answers are a valuable part of this research.
31.07.2020 – 07:26

Submit your survey.
Thank you for completing this survey.