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The use of P3b as an indicator of neurophysiologic change from subconcussive impacts in football players

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Abstract

There is a growing appreciation in research that subconcussive impacts may affect cognitive functioning. Canadian University football players (n=45) were separated into three groups based on their position/skill (small skilled, big skilled and big unskilled). An impact measuring device (GForceTracker) was used to record the number of impacts that each player experienced in a season. Player groups were separated into two levels of impact exposure: low and high. Players completed baseline, midseason, postseason, and follow-up neurophysiological tests (four months later) to measure P3b amplitude in response to a visual oddball paradigm, and high versus low impact subgroups for each player group were compared. Small skilled and big skilled players showed significant decreases in P3b amplitudes at midseason and postseason, reflecting decreased attentional resources allocated to the task. No skill group exhibited a significant change from baseline at follow-up, illustrating that in-season cognitive function deficits appear to recover in the offseason.

Keywords

Subconcussive head impacts, football, P3b, concussion

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1 Introduction

1.1 Concussion

Dr. Robert Cantu, the foremost expert on concussion diagnosis and management, described in a review paper that concussions were first brought to society's attention as a medical condition in 1904 through President Roosevelt's threat of banishment to American football[20]. At the time, the main indicator for a concussion was loss of consciousness[98, 112, 123]. As time passed and the understanding of concussions grew, so has the definition of a concussion. Currently, a concussion is defined as a complex pathophysiological process that affects the brain and is induced by biomechanical forces[87]. It can result from a direct impact to the head/neck or from an indirect impact to the body that transmits an impulsive force to the head[72, 87, 148]. The diagnosis for a concussion involves the assessment of 22 clinical symptoms, physical signs, cognitive impairment, behavioural changes, and sleep disturbance by a trained health professional[87]. The 22 clinical symptoms are: headache, "pressure in head", neck pain, nausea or vomiting, dizziness, blurred vision, balance problems, sensitivity to light, sensitivity to noise, feeling slowed down, feeling like "in a fog", "don't feel right", difficulty concentrating, difficulty remembering, fatigue or low energy, confusion, drowsiness, trouble falling asleep, more emotional, irritability, sadness, and nervous or anxious[86]. The breadth of this array of clinical indicators speaks to the diversity of the etiology of concussions and the large variety of factors that affect the brain. A recent review concluded that in order to better understand what changes occur in the brain, input variables such as head accelerations are used as surrogate parameters to measure head impacts and investigate their association with concussion[72].

When a head is impacted, either directly or indirectly, it sustains combined linear and rotational accelerations[72, 90]. Early animal studies by Gurdjian et al. indicated that linear acceleration was the primary cause for head injury[50, 52]. Holbourn et al. acknowledged rotational acceleration as a cause for head injury[65] and later animal studies by Ommaya et al.[98] and Gennarelli et al.[42, 44] concluded that head injury was not caused by pure linear or pure rotational accelerations; rather, it was caused by the brain's response to complex interactions between linear and rotational head accelerations[72]. However, these acceleration measurements were performed on primates[44, 98] and cadavers[51]. Animals do not share the same physiology as humans and cadavers do not have any physiologic response when impacted. Thus, measurements from human participants were needed. Purposefully exposing human beings to potentially injurious head impacts is not ethical so professional sport was explored as an arena for research due to its relatively common frequency of head impacts.

1.2 Head Impact Biomechanics in the Sport of Football

A recent review estimated that there are between 1.6 million and 3.8 million sports-related concussions in the United States annually,[77] with the highest proportion of concussions being reported in football[45, 80, 109, 119, 126]. The mechanisms of injury underlying the high concussion rate in the sport of football were unclear, so a variety of metrics have been proposed to quantify head impact exposure such as peak linear head accelerations, total number of impacts, and linear acceleration thresholds[143]. Researchers at University of California at Davis[93] and Evanston Hospital[111] quantified head accelerations during football competitions in the early 1970s. Moon et al collected data from five players during scrimmage practices and actual conference games[93]. They report that the peak linear accelerations in university football can exceed 1000 g. Reid et al collected head acceleration measurements from one middle linebacker during seven Big Ten Conference games, and observed peak accelerations between 40 and 230 g[111]. In a follow-up study, they reported that one player sustained 650 head impacts during gameplay over the course of three university football seasons, including twelve high intensity impacts that produced accelerations between 180 and 400 g[112]. They observed a single concussion which occurred following a 188 g impact[111]. Linear accelerations of that magnitude were between 2.3 and ten times as large as any earlier measurements on cadavers or animals[53] and were likely inflated due to the low resonant frequency of their instrumentation. These early studies in football only examined the linear accelerations of the head.

Recent studies have reconstructed concussion-inducing impacts in the National Football League (NFL) via video analysis[96, 100, 101, 132]. Video data were used to calculate the angle and velocity of the impacts and then the impacts were reconstructed in a laboratory setting using Hybrid-III (HIII) anthropomorphic test devices (ATDs). Accelerometers were located at the centre of mass of the ATD heads. The peak head acceleration in these reconstructed concussive impacts was 98 ± 28 g, which was significantly greater than impacts received by uninjured players[100, 101]. However, the findings of these studies were limited to specific impacts of NFL athletes that could be viewed on video, and they focused on concussive events.

1.3 The Head Impact Telemetry System

Video analysis and laboratory impact reconstruction are labour intensive and limited to ATD biofidelity assumptions and validation from video that has limited sample rate (30 Hz)[96, 100, 101, 103, 131, 150]. Real-time high-resolution data regarding head impacts and accelerations of football players were needed, and the Head Impact Telemetry (HIT) System (Simbex, Lebanon, NH) was created. The HIT System consists of six linear spring-mounted accelerometers that are designed to fit inside a Riddell VSR-4 L or XL football helmet (Riddell, Elyria, OH) and wirelessly record and transmit head acceleration data to a sideline computer[34]. These data are processed using a proprietary algorithm to calculate the peak linear and rotational acceleration magnitudes at the head's centre of mass and the location of each impact[22, 26]. Peak rotational acceleration is calculated by multiplying the vector product of peak linear acceleration and a point of rotation 10 cm below the centre of mass of the head and iteratively optimizing the sum of squared error between each accelerometer value and the expected acceleration[26]. The HIT System's head impact kinematics has been validated in computer simulations[26] and by comparing resultant head linear and rotational accelerations measured between the HIT System and an instrumented HIII head form from a linear impactor[5]. However, a recent study performed by Jadischke[67] presented evidence that the HIT System does not yield accurate data. A pressure-sensing cap was used to examine the fit of the helmet to a player's head. These measurements were then used to properly fit a HIT-instrumented helmet to a HIII head form and perform testing via a linear impactor. Previous studies had always used a medium-sized helmet[5, 82, 96] while Jadischke's pressure cap indicated that a large-sized helmet should be used as this was representative of how players wore their helmets in a comfortable pressure range. It was also noted that previous studies reported the correlation between the HIT System and HIII using relative errors, which tended to offset large positive and negative deviations. Finally, the linear acceleration of any impact recorded by the HIT System had a large range of inaccuracy. They report that an impact that HIT records as 100 g would actually correspond to head accelerations that are less than 85 g or greater than 115 g, 55% of the time[67]. According to one study, this range of head accelerations represents a 52-70% risk of concussion[150]. This high degree of uncertainty would likely result in some concussions being missed while other non-concussed players would be excluded from play.

Notwithstanding these limitations, the HIT System is the most commonly used system for measuring head impact kinematics[96]. This device has been used to quantify linear and rotational head accelerations experienced by football players at collegiate[6, 16, 27, 28, 34, 35, 40, 49, 56-58, 60, 84, 85, 92, 97, 115, 117, 118], high school[6, 8-12, 14, 15, 38, 49, 83, 118, 124], and minor[23, 128, 129] levels over the course of complete seasons. While the studies that have implemented the HIT System have focused on peak linear accelerations and their effect on head injury, rotational accelerations have been overlooked. Rotational accelerations occur from a linear force acting at a distance from the center of rotation [116]. Early research has associated concussions with rotational acceleration of the head and impacts that cause shear stress in the brain due to coronal motion[43, 44]. More recently, the head kinematic data from reconstructed NFL impacts[100, 101] were used as input into a comprehensive finite element computer model of the human head: the Wayne State University Brain Injury Model (WSUBIM)[149, 150]. This study found that intracranial pressure was largely a function of linear acceleration. They also found that shear stress was more sensitive to rotational head acceleration in the midbrain (thalamus and brainstem) and relatively insensitive to translational acceleration[148, 151]. Other finite element model studies have investigated large cumulative strains in the brain induced by large magnitudes of rotational velocity[69] as well as examined impact direction and duration and rotational velocity and their relationship with strain-induced brain injuries[140]. These studies provided evidence that both rotational velocity and rotational acceleration contribute to the cause of concussions.

In an effort to improve estimates of the head centre of mass acceleration and gather better rotational measurements, a device combining the HIT System with six additional accelerometers was developed to measure six degree of freedom (6DOF) head accelerations in football player impacts[114]. This device measures linear and rotational accelerations at the centre of mass of the head and was validated with linear impactor testing. Similar 6DOF devices were incorporated into a mouth guard and combined linear accelerometers and gyroscopes to approximate head kinematics during impact[4, 17, 62, 146]. One study reasoned that the mouth guard is located closer to the centre of mass of the head than an accelerometer mounted to the crown of the helmet and so it may provide a better representation of the head's centre of mass acceleration during impact than a helmet-mounted accelerometer[62]. However the mouth guard devices cannot clearly distinguish between impact and non-impact events in a laboratory setting with ideal conditions[62], and have not been tested during gameplay. The scope of the on-field data was limited to a player wearing their mouth guard properly and clenching down with their teeth for every impact and may require hit verification through video.

1.4 Hit Count

While many studies have focused on the kinematic aspect of head impacts, others have focused on examining athletes' hit count during a season. For example, the HIT System has been used to monitor 42 high school football athletes' head impact exposure over the course of a single season[12]. These data were used to suggest that contact should be limited in practices to reduce the number of head impacts that athletes sustain during the season. Another study made comparable conclusions based on studying 20 college level football athletes in one season[113].

One study of two high school football teams over two seasons used the HIT System to count the number of subconcussive impacts that the players received during practices and games. They found a decrease in visual working memory in relation to head impact exposure[120]. An associated paper from this study found altered functional connectivity using functional Magnetic Resonance Imaging (fMRI) in football athletes compared to noncontact sport athletes[1]. Another high school football study used the HIT System, neurocognitive testing, and fMRI to evaluate neurocognitive and neurophysiological deficits as a function of head impacts[124]. Two groups of athletes were compared – concussed and non-concussed. While finding deficits in neurocognitive and neurophysiological functioning in the group of concussed athletes, deficits were also found in half of the non-concussed group creating a third study group without observable symptoms of concussion but still exhibiting cognitive impairments.

Similarly, a study of 214 college football and ice hockey athletes used the HIT System to monitor head impact exposure over a single season[84]. Contact athletes were compared with noncontact sport athletes and all participants completed a cognitive screening test pre- and postseason. They reported significant differences for main effect of time (preseason and postseason) and main effect of athlete type (non-contact vs. contact). As well, contact athletes performed significantly poorer on a measure of new learning compared to noncontact athletes.

1.5 The GForce Tracker

GForce Tracker (Markham, ON, Canada), has developed a device with similar functionality to the HIT System and the instrumented mouth guard. It measures 6DOF head impact kinematics. The GForce Tracker (GFT3) device is attached to the inside shell of football players' helmets and it collects the linear acceleration, rotational velocity and impact location of every impact above a user-defined threshold.

Figure 1.1: The GForce Tracker relative to a quarter. Coordinate system is shown in red, with the circled axis directed into the page.

The GFT3's accuracy in measuring head accelerations has been evaluated through linear impactor testing[19]. This evaluation showed that the head linear acceleration magnitudes were approximately 49% of the helmet accelerations recorded by the GFT3. This is similar to a study on hockey helmets that reported comparable magnitudes around 68%[74], but quite different than one study that performed helmet to helmet impacts in a laboratory with the HIT System and reported that the head accelerations were only 10% of the helmet accelerations[81]. It is unclear whether the differences may be due to experimental factors (such as helmet to helmet impacts versus impactor tests) or instrumentation differences. Previous research in the Joint Biomechanics Laboratory at Western University has developed a correction algorithm to predict head centre of mass kinematics from the GFT3 measurements[19].

1.6 Electroencephalogram and Its Use in Measuring Concussion

Electroencephalogram (EEG) is the neurophysiologic measurement of brain electrical activity. Electrodes are placed on the scalp to measure changes in electrical activity originating from the brain. It is noninvasive and relatively inexpensive, and therefore it has become a common tool to examine brain function in concussion[125].

There are several studies of human EEG during head impact in football that were published in the late 1960s and early 1970s[66, 111, 112]. These studies focused on the linear forces and time of the impacts. A total of two concussions were captured on EEG during impact in these studies. Two of the studies reported the appearance of abnormal EEG theta rhythms after severe head impact, but concluded no head trauma had occurred[111]. EEG has been used in animal models to measure induced concussions in an effort to understand the immediate physiologic response to a head impact[32, 33, 39, 61, 71, 91, 136, 138, 142]. EEG measurements have been studied closely following concussions in boxers[33, 59, 70]. Interestingly the boxers showed little or no noticeable changes in EEG immediately following a concussion. Also, there was no statistically significant correlation between EEG changes and the number of fights or career length. EEG has also been used to compare control against concussed participants[31, 48, 134]. Other studies have used EEG to examine the brain at certain time points during recovery from concussion[75, 135]. EEG has been compared with clinical signs and symptoms; however, some clinical discrepancies exist despite normal EEG findings[137, 141]. Conversely, some neuropsychological deficits exist despite normal clinical presentation[25, 79, 127]. All of this has led some authors to conclude that EEG is a poor diagnostic tool for concussion[41, 105, 134].

1.6.1 Event-Related Potentials

Event-related potentials (ERPs) are a time-locked EEG technique in response to a stimulus[36]. ERPs are largely used in research protocols to investigate cognitive functioning and are resistant to practice effects. Event-related potentials are the averaged EEG signal recorded after a stimulus is presented. These averaged signals are made up of different waves that are named according to their polarity (P for positive and N for negative) and their latency (i.e. P300 is a positive wave evoked 300 ms after presentation of a stimulus).

1.6.2 The P3 Wave

The best-known paradigm among the tasks used in ERPs is the Oddball paradigm. It consists of the presentation of two stimuli (auditory or visual), each having different probabilities of happening (frequent and infrequent). The frequent target stimulus elicits a strong positive P300 wave which is commonly referred to as P3a[47]. The amplitude of the P3a wave is associated with engagement of attention, stimulus recognition, and the processing of novelty stimuli[76, 106]. When the infrequent stimulus occurs, subjects must give a physical response (i.e. press of a button). This infrequent target stimulus elicits a strong positive P300 wave which is commonly referred to as P3b. The amplitude of the P3b wave does not directly measure cognitive performance, but is associated with the amount of attentional resources allocated to a task, information processing, and working memory[76, 106, 122]. The P3b wave is a deflection after stimulus onset which has a higher peak amplitude than the P3a response[47]. The latency of these P3 responses has also been studied[3, 99, 110, 121].

1.7 Eliciting P3 to Measure Concussion

The P3 wave has been well studied pertaining to changes in cognitive function associated with development[63, 130], aging[88], and health behaviours[64]. Changes in P3 have also been evaluated in the acute stages of concussion[7, 78]. Dupuis et al.[37] found deficits in P3b amplitude following a sport-related concussion in symptomatic athletes compared to asymptomatic athletes and non-concussed athletes. Another study reported a delayed P3 response in both symptomatic and asymptomatic athletes compared to control participants, despite normal clinical cognitive evaluations[48]. A similar study with the same athletes tested found an attenuation of the P3b component in concussed athletes compared to control participants, and symptomatic athletes showed a greater reduction than asymptomatic athletes[78]. The reduction in P3b amplitude observed in these studies represents a reduced amount of attention resources allocated to the task and has been observed in other clinical populations with deficits[46].

ERPs and the P3b wave have also been utilized to evaluate the effects of multiple concussions and overall long-term effects of concussion on athletes. For example, a study compared the P3b responses for athletes with a history of concussion to those without[13]. They report significant decreases in P3b amplitudes in the athletes with a history of concussion even though both groups performed equally on a clinical cognitive assessment. Another study compared healthy former athletes who had last suffered a concussion over 25 years ago to age-matched former athletes with no concussion history[31]. They found significantly delayed and attenuated P3 waves in the athletes with a concussion history.

1.8 Subconcussive Impacts

A large amount of research has used the framework that concussions are caused by one "big hit"[14, 55, 56, 85, 102]. Studies examining concussive hits in professional and college football have not been able to pinpoint an exact threshold that will lead to concussion, but have established a range in which there is a greater likelihood of concussion[100]. Others have explored the effect of multiple concussions sustained over a career has on the brain[24, 54] and even linked this to a deadly disease – chronic traumatic encephalopathy (CTE)[89] and neurodegenerative conditions such as ALS[21, 139]. Many studies observing head impact exposures in collegiate football have measured impacts that were considerable in magnitude but did not result in concussion[18, 28, 29, 92]. During a Canadian university football game, players receive an average of 17.8 impacts to the head with an average rotational acceleration of 1846.41 rad/s^2 and average linear acceleration of 21.53 g[18]. There is a lack of research on the effects of these subconcussive impacts on the human brain. A player's health risk is further affected by the number (history) of impacts a player has received over their career, the amount of impacts in a short period of time, and the magnitude of each impact. As a player's sub-concussive impact exposure increases, there may be changes occurring to their brain that do not result in concussive symptoms. Since these impact exposures accumulate over long periods of sports play, and each impact's effect does not present as an acute injury, then the overall effect on the player will be gradual and difficult to notice in their behaviour. ERP measurements can distinguish changes in brain activity before they manifest as physical symptoms[25, 79, 127], and accordingly may be a powerful tool for investigating the effects of accumulated sub-concussive head impacts.

2 Purpose Statement and Hypotheses

2.1 Purpose Statement

The purpose of this thesis was to determine if Canadian university football players experience changes in cognitive functioning, as reflected in their P3b event related potentials, in relation to the number of subconcussive impacts that they receive over the course of a single season.

2.2 Hypotheses

1) Players that experience a higher number of impacts throughout the season will show greater deficits in their P3b amplitude than players that experience a lower number of impacts.

2) There will be a relationship between changes in P3b amplitude at midseason and postseason time points and the number of head impacts depending on player skill group.

3) All players will show a return to baseline P3b amplitude at the follow-up time point.

3 Methods

3.1 Participants

Members of the varsity football team during the Fall 2015 Canadian Interuniversity Sport (CIS) football season were eligible to participate in this study, and Western University's Human Subjects Research Ethics Board approved the protocol. There were 110 football players on the 2015 Western University Mustangs varsity football team. Forty-seven of these players made up the dress roster that competed in games. The coaching staff advised which players would consistently play in games throughout the season and the positions that they would play. Fifty-six players volunteered to participate in this study, and they all provided formal written informed consent. They represented players from various football positions who participated in training camp, practices and in games. There were ten running backs (including two quarterbacks), nine receivers, nine offensive linemen, eight defensive linemen, ten linebackers, and ten defensive backs. Participants' age range was narrow but mass and height varied according to player position (Table 3.1). The helmets of these players were equipped with sensors that measured the magnitude of each impact that the players received during the season. Five of these players were subsequently withdrawn from the study based on the coaching staff's assessment that they would have limited playing time. In addition, two participants left the team at separate times during the season and one participant received a season-ending injury.

Table 3.1: The number of players per position and the average and standard deviation of their body masses, heights and ages for each position

Position	Number of Players	Mass (kg)		Height (m)		Age (yrs)	
		Mean	SD	Mean	SD	Mean	SD
Defensive Back	10	84.05	3.96	1.81	0.02	22.34	1.05
Linebacker	10	97.48	4.03	1.82	0.04	21.42	1.39
Defensive Line	8	115.50	14.94	1.88	0.05	22.10	1.21
Offensive Line	9	127.96	13.15	1.91	0.06	21.67	0.76
Runningback	10	94.08	7.80	1.82	0.05	21.67	1.32
Wide Receiver	9	86.38	5.35	1.85	0.07	21.90	1.15
All Positions	**56**	**101.31**	**19.25**	**1.85**	**0.06**	**21.80**	**1.23**

Participants performed neurophysiological testing (eVox System, Evoke Neuroscience, New York, USA) at four separate times during the study – a preseason baseline (before training camp began), a midseason test (after five games had been played), a postseason test (after the conclusion of the season; ten games had been played), and a follow-up test four months after the end of the season. Fifty-one players completed baseline neurophysiological testing. For the two participants who left the team during the season, one had completed two neurophysiological tests and the other had missed the baseline testing. Another participant missed the postseason test time point due to personal reasons. Two participants did not undergo the March follow-up tests as they were not available.

In an effort to increase the number of participants with a complete data set (helmet devices and completed neurophysiological tests), four players who were regular starters in games were removed from the study due to incomplete baseline neurophysiological tests. However, the devices in these players' helmets were retained to collect representative head impact exposures for players in that position. The device of the participant who received a season-ending musculoskeletal injury was reassigned to another participant who underwent a baseline neurophysiological test and played the same position. The new player did not have a device in his helmet and accordingly his head impacts up to this point had not been recorded. In this case, his impacts for the first part of season were assumed to be identical to the player that he replaced. The participant that suffered the season-ending injury remained in the study - although he did not participate in any more practices or games, he did complete neurophysiological testing at all four time points.

3.2 Helmet Instrumentation and GFT3 Measurements

The GForce Tracker (GFT3, Artaflex Inc., Markham, ON, Canada) is 52 mm long, 28 mm wide, 10 mm high, and weighs 20 g. It contains a tri-axial accelerometer, a tri-axial gyroscope, a lithium ion rechargeable battery, and on-board memory for storing up to 400 impacts. The accelerometer has a range of ± 200 *g* and a 1 *g* resolution on each axis while the gyroscope measures rotational velocities with a range of ± 2000 °/s. The GFT3 was triggered when any of the three orthogonal linear accelerometers detected an acceleration greater than the user-defined threshold; this study used a threshold of 15 *g* which is consistent with best practices defined in a recent review.[73] The device recorded data for a 40 ms window for each impact. The first 8 ms of data preceded the trigger, and the remaining 32 ms of data followed the trigger. The linear acceleration signals were sampled at 3000 Hz and low-pass filtered with a 300 Hz anti-aliasing filter. The rotational velocity signals were sampled at 800 Hz and low-pass filtered with a 100 Hz anti-aliasing filter. These sample rates are consistent with recent recommendations[147]. Each impact was time stamped and recorded to the onboard memory of the GFT3.

The participants' helmets were instrumented with one GFT3. It was adhered to the inside of the helmet, right of the crown cushion, using an industrial strength re-closeable fastener (3M™ Dual Lock™ Re-closeable Fastener SJ3551 400 Black, 3M Global Headquarters, St. Paul, MN). This location and mounting are similar to previous studies[2, 18, 94, 133] and have been validated against measures recorded at the centre of mass of the head using a Hybrid III anthropometric test dummy headform[19]. Helmets were fitted by the team's equipment manager.

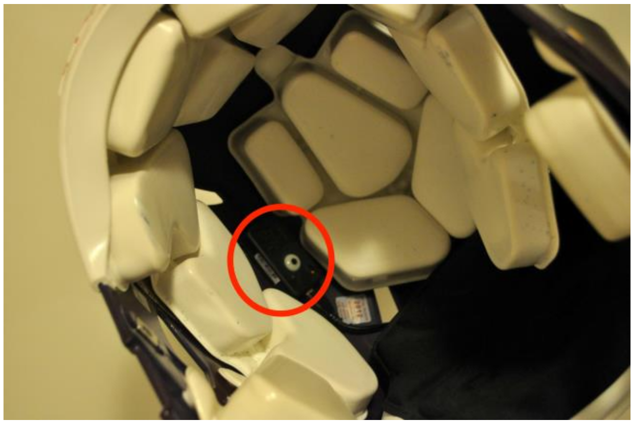

Figure 3.1: Figure depicts a GFT3 device, circled in red, mounted to the right of the crown cushion.

3.3 Data Collection Protocol

3.3.1 Practices

Participant attendance was recorded during every practice. All of the GFT3 devices were turned on remotely before the scheduled practice start time. During practice, the timing of each scheduled practice activity was recorded. A custom LabVIEW program used these time recordings to delete any impacts that were measured by the device when the participant was not taking part in practice drills or the helmet was not on the participant's head. Upon the completion of practice, the devices were powered off remotely and participants returned their helmets to the charging racks in the team locker room. The GFT3 data were wirelessly transmitted to a laptop after every practice. The impact data were uploaded to the GFT3's cloud-based Internet software for storage. A summary file of every time stamped impact was exported to Microsoft Excel 2011 (Microsoft, Redmond, WA, USA). Each summary file contained the peak linear acceleration, peak angular velocity, max HIC_{15}, GSI, and location for each impact on one sheet. The linear acceleration time series data and angular velocity time series data for all of the impacts from that practice were recorded on two additional sheets. The devices remained inside the helmets while they were connected to a micro USB cord and wall mount adapter to charge.

3.3.2 Games

Participant attendance was recorded at every game. All of the GFT3 devices were turned on remotely while the participants were on the field before the start of the game. A custom LabVIEW program was used to record which participants were on the field for each play of the game. These data were later used to ensure that only impacts occurring to participants competing on the field were included for analysis. Upon the completion of each game, the helmets were returned to the charging racks and the same procedure was followed for downloading data and charging devices as after practices.

3.4 EEG Measurements

3.4.1 Instrumentation

The eVox System (Evoke Neuroscience, New York, New York, USA) is a portable hardware and software system that consists of all necessary components to record electrophysiological data and conduct basic biofeedback modalities. The components are housed in a protective shipping and travel case that allowed for the participants to be tested at TD Stadium and Thames Hall Room 2141 of Western University, as appropriate. Two units were used for the testing in this study.

Each eVox unit consisted of one base station laptop, a tape measure, an amplifier and its charging kit, two sets of ear bud earphones, medical tape, a response button, one medium and one large cap (Electro Cap International, Eaton, Ohio), electrode gel (Elecro-Gel, Electro Cap International, Eaton, Ohio) and skin preparation gel (NuPrep, Weaver and Company, Aurora, Colorado).

3.4.2 Testing Procedure

The measuring tape was used to measure the participant's head circumference in order to select the correct cap size for the participant. The EEG cap was applied to the head of the participant and connected to the amplifier. The cap is constructed such that the 19 electrode locations correspond to specific scalp location positions according to the 10-20 International System for electrode placement[68]. The amplifier is a battery powered device that connects to the EEG cap to measure EEG and ECG data and transmits it wirelessly to the base station computer for recording. NuPrep abrasive skin prep was applied to the ear lobes of the participant to improve contact and decrease impedance for the ear clips. Electro-Gel was inserted in the ear clips which were then placed on the ear lobes. An alcohol swab was used to rub the skin below the clavicle on the participant's left side of their chest in preparation for the ECG sensor. Electro-Gel was then inserted in the ECG electrode and taped gel side down below the participant's clavicle. Electro-Gel was applied to each of the 19 electrodes on the EEG cap with a blunted needle. Connection quality was displayed on the laptop screen for each of the 19 cap electrodes, both earlobe electrodes and the ECG electrode. If any of the connections exhibited poor quality, then additional gel was inserted. The test did not proceed until all sites indicated that a good connection had been established. The ear bud headphones provided auditory instructions, prompts, and stimuli to the subject throughout the assessment process. Upon completion of every test, each cap and its electrodes were thoroughly washed with soap and any excess Electro-Gel removed before being used again in accordance with manufacturer recommendations. Blunted needles were disposed of after each use (one per participant).

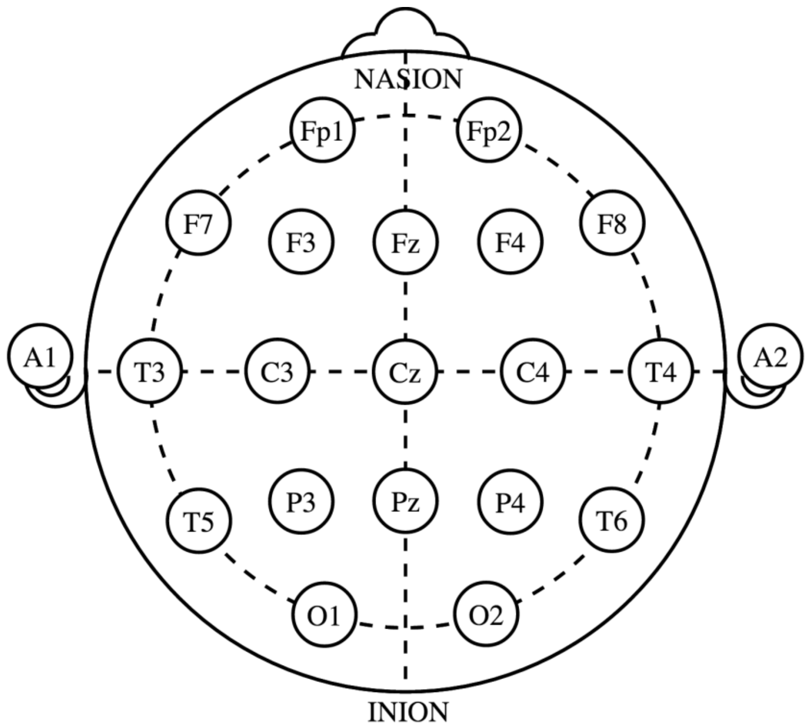

Figure 3.2: Illustration showing the 10-20 System for scalp electrode placement during an EEG test. F, T, C, P, and O stand for frontal, temporal, parietal, central, and occipital. Even numbers refer to positions on the right hemisphere and odd numbers refer to positions on the left hemisphere.

3.4.3 Neurophysiologic Tests

Participants completed three tasks during each test session: Eyes Open Relaxed, Eyes Closed Relaxed, and the Oddball paradigm. During the Eyes Open Relaxed task, each participant was instructed to stare at the computer screen for five minutes with their eyes open. For the Eyes Closed Relaxed task, the participant spent five minutes with their eyes closed, staying awake. During these two tests, participants were instructed to sit as still as possible, minimizing facial and head movement, in order to reduce movement artifact. Finally, participants performed the Oddball paradigm for the remaining ten minutes of the testing session. Two visual stimuli (a medium blue circle and a large blue circle) were presented in a random series such that one of them occurred relatively infrequently (the large blue circle). The participants were required to distinguish between the stimuli by pressing the response button when the large blue circle appeared on the screen. The participants completed a short tutorial and received feedback on their performance before the actual test commenced.

3.5 Data Analysis

P3b waves were acquired from 19-channel tin sensors using a ground from linked ear electrodes at a sampling rate of 250 Hz. All electrode impedances were measured below 10 kΩ. P3b wave signals from the midline parietal electrode (indicated as Pz in Figure 3.3) were analyzed for peak amplitude. Amplitude was measured as the difference between the mean pre-stimulus baseline and maximum peak amplitude. The time window used to identify P3b was 250 to 500 milliseconds. Only data associated with correct stimulus identification were included in the analysis. Eye blinks and eye movement artifact were corrected using proprietary digitized algorithms and visual analysis to ensure consistent artifact rejection across all participants.

When a participant finished their neurophysiological testing, their raw EEG data was uploaded wirelessly from the base station laptop to a secure, password protected cloud. The raw EEG data were then analyzed and reports created that could be accessed through the cloud. If a participant had more than two indiscernible scores for their P3b amplitudes, they were excluded from the statistical analysis.

P3b amplitude changes were calculated relative to baseline. Each subsequent test was subtracted from the participant's baseline test. A negative value indicated a decrease in P3b amplitude from baseline while a positive value indicated an increase in P3b amplitude from baseline.

Participants were placed into high impact and low impact groupings at each skill level for all three time points depending upon their total number of impacts at the end of season. High impact players were distinguished from low impact players by calculating the median number of impacts received as a group. Players who had more impacts than the median were labelled high impact while those below the median were low impact. If the median statistic fell on a player's exact number of impacts, then the mean of the group was then used to decide the placement of that player. If the number of impacts for that player was less than the group mean, that player was grouped as a low impact player. If the number of impacts for that player was more than the group mean, that player was grouped as a high impact player.

Midseason neurophysiological tests were performed after the team had competed in five games. Individual players had participated in between 26 and 31 contact practices depending when they completed their midseason neurophysiological test. The midseason assessment of the number of impacts was tallied up to the last impact that the players received before their midseason neurophysiological test.

Postseason and follow-up tests were performed after the team had competed in ten games and 42 contact practices.

3.6 Statistical Analyses

Only participants who experienced impacts in at least one practice, underwent a neurophysiological baseline test, and had at least two discernible P3b amplitudes were included for statistical analysis. A total of 45 players met these inclusion criteria. A Shapiro-Wilks test was used to determine the normality of the distribution of the change in P3b amplitudes for each testing point at a significance level α of 0.05. Homogeneity of variances was assessed by Levene's test for equality of variances at a significance level α of 0.05. Outliers were determined via a boxplot analysis. Means and standard deviations for the changes from baseline in P3b scores were determined. Analysis of variance tests could not be performed on this data set due to the unequal sample sizes in each group and the test's inability to account for missing data. Thus, one-tailed independent-samples t-tests were performed to assess the specific *a priori* hypotheses of whether there were statistically significant differences in change in P3b amplitudes for high versus low impact frequency at the midseason and postseason testing points as well as comparing the P3b amplitudes of the different player groups at baseline. Two-tailed independent-samples t-tests were performed to assess the specific *a priori* hypothesis of whether there were statistically significant returns to baseline P3b amplitudes for high versus low impact frequency at the follow-up time point. Given the preliminary nature of this experiment and the relatively limited amount of data, no post hoc Bonferroni-style adjustments were performed to correct for experiment-wise type I errors. This approach has been advocated when multiple tests are performed, but that the variables are independent[104]. Player skill and player mass defined the between-subjects factor and comprised of three levels: small skilled, big skilled, and big unskilled[12, 95]. The small skilled group included wide receivers and defensive backs. The big skilled group included linebackers, runningbacks, fullbacks, and quarterbacks. The big unskilled group included offensive and defensive linemen. These three skill groups were expected to experience similar number and magnitude of impacts[12, 18, 95], and the nearly equal number of members in each group will make the statistical analysis robust. All statistical tests were performed using R Studio 2015 (RStudio, Inc., Boston, MA) and the level of significance was set at an alpha level of less than 0.05 *a priori*.

4 Results

In the following sections, data are presented as mean ± standard deviation, unless otherwise stated. Box plot analyses were used to determine any outliers and are reported accordingly. Change in P3b scores for each level of impact frequency were normally distributed, as assessed by Shapiro-Wilk's test ($p>0.05$), and there was homogeneity of variances, as assessed by Levene's test for equality of variances ($p>0.05$), at all time points.

Postseason tests were completed an average of 10.58 ± 10.04 days after the final impact to a player's head was received. The wide spread of this data is explained by three outliers of 24, 29, and 68 days since last impact. Two of these players were injured during the season so did not continue to receive impacts but continued to complete the neurophysiological tests and one player who was not available for a postseason test for over three weeks due to personal reasons.

Follow-up tests were completed an average of 116.89 ± 11.87 days after the final impact to a player's head was received. The wide spread of this data is explained by two outliers of 182 and 141 days since last impact. These were the two players injured during the season.

4.1 P3b Amplitudes Compared to Baseline

4.1.1 Small Skilled Group

P3b amplitudes for small skilled high impact players (–7.46 ± 7.89 μV) had a greater decrease from baseline to midseason than did P3b scores for low impact players (1.23 ± 6.25 μV), a statistically significant mean difference of –8.69 μV (95% CI, –∞ to –2.68, $t(15) = -2.53$, $p=0.011$) (Tables of P3b amplitudes are reported in the Appendix).

P3b amplitudes for small skilled high impact players (–4.36 ± 2.05 μV) had a greater decrease from baseline to postseason than did P3b scores for low impact players (–0.19 ± 5.51 μV), a statistically significant mean difference of –4.17 μV (95% CI, –∞ to –0.54, $t(15) = -1.88$, $p=0.041$) (Tables of P3b amplitudes are reported in the Appendix).

P3b amplitudes for all small skilled players did not show a significant difference from baseline to follow-up ($p>0.05$, tables of P3b amplitudes are reported in the Appendix).

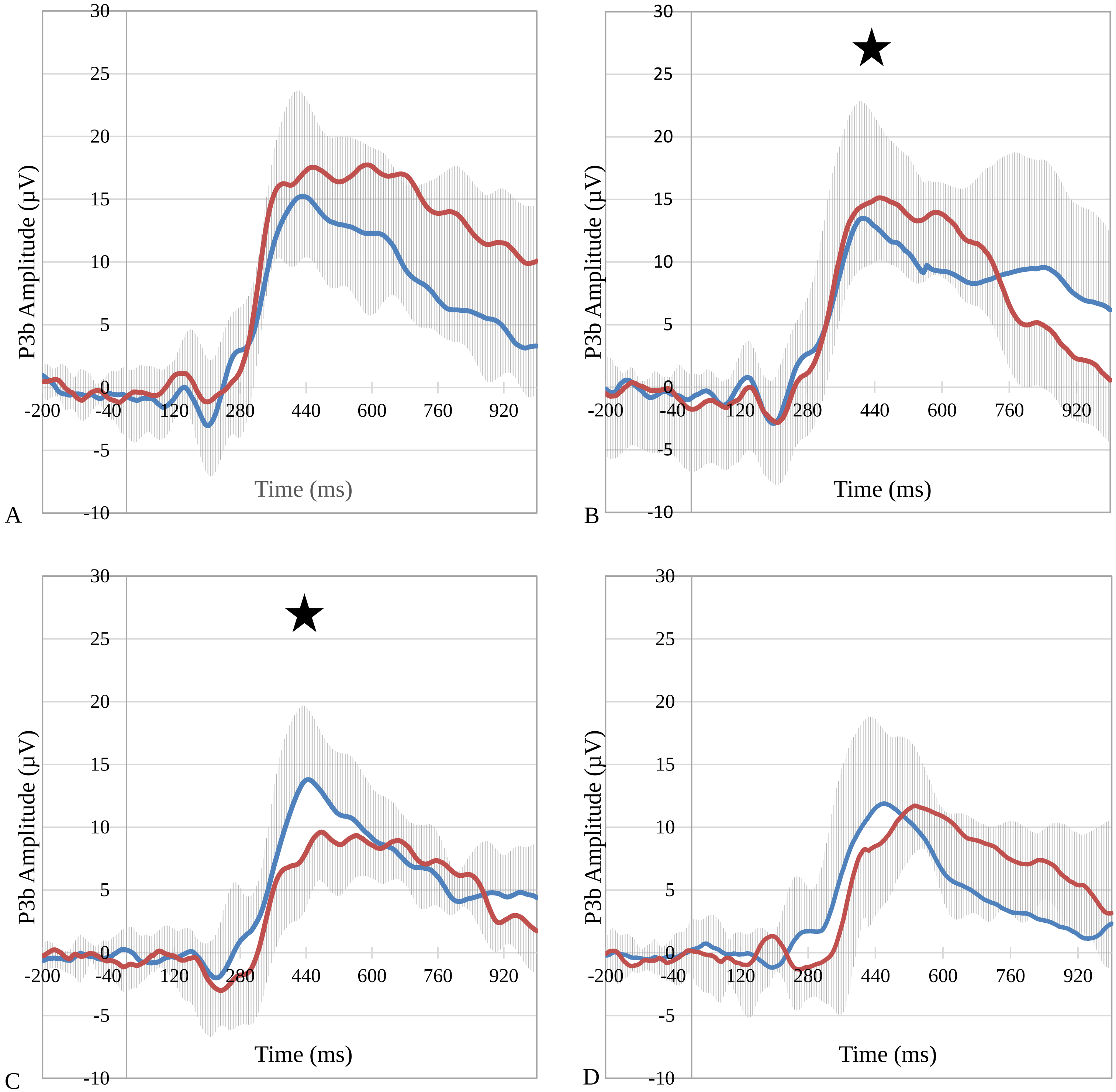

Figure 4.1 a) Baseline, b) Midseason, c) Postseason, and d) Follow-Up mean P3b amplitudes for small skilled group. High impact group average is in red (minus 1 standard deviation) low impact is in blue (plus 1 standard deviation). The star denotes a statistically significant difference from baseline between impact groups.

4.1.2 Big Skilled Group

P3b amplitudes for big skilled high impact players (–2.87 ± 2.25 μV) had a greater decrease from baseline to midseason than did P3b scores for low impact players (1.10 ± 3.84 μV), a statistically significant mean difference of –3.97 μV (95% CI, –∞ to –1.04, $t(13) = -2.40$, p=0.016) (Tables of P3b amplitudes are reported in the Appendix).

P3b amplitudes for big skilled high impact players (–2.27 ± 1.74 μV) had a greater decrease from baseline to postseason than did P3b scores for low impact players (0.27 ± 2.19 μV), a statistically significant mean difference of –2.54 μV (95% CI, –∞ to –0.71, $t(13) = -2.33$, p=0.020) (Tables of P3b amplitudes are reported in the Appendix).

P3b amplitudes for all big skilled players did not show a significant difference from baseline to follow-up (p>0.05, tables of P3b amplitudes are reported in the Appendix).

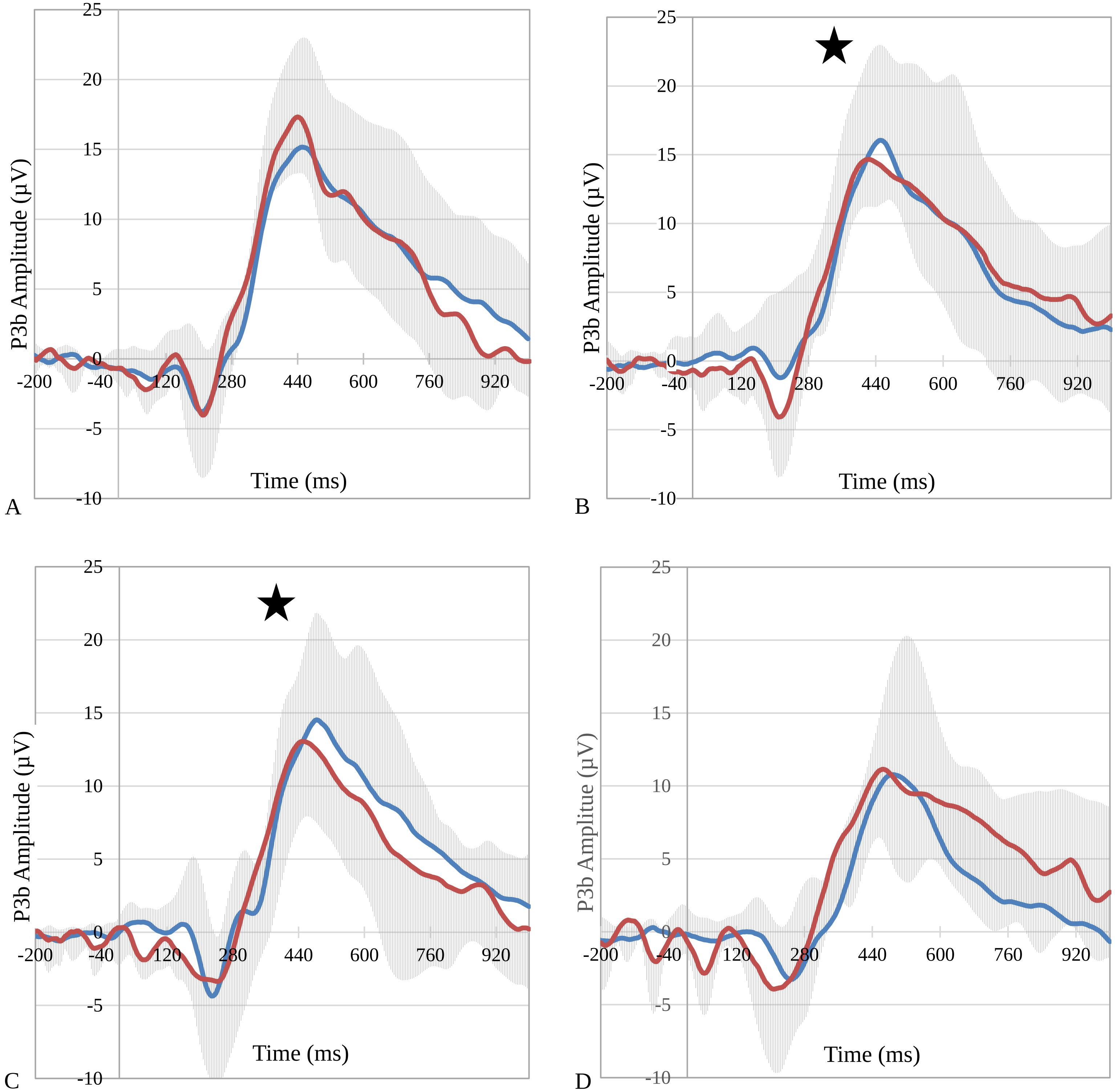

Figure 4.2 a) Baseline, b) Midseason, c) Postseason, and d) Follow-Up mean P3b amplitudes for big skilled group. High impact group average is in red (minus 1 standard deviation) low impact is in blue (plus 1 standard deviation). Star denotes statistically significant difference from baseline between impact groups.

4.1.3 Big Unskilled Group

P3b amplitudes for all big skilled players did not show a significant difference from baseline to midseason, baseline to postseason, nor baseline to follow-up ($p>0.05$, tables of P3b amplitudes are reported in the Appendix).

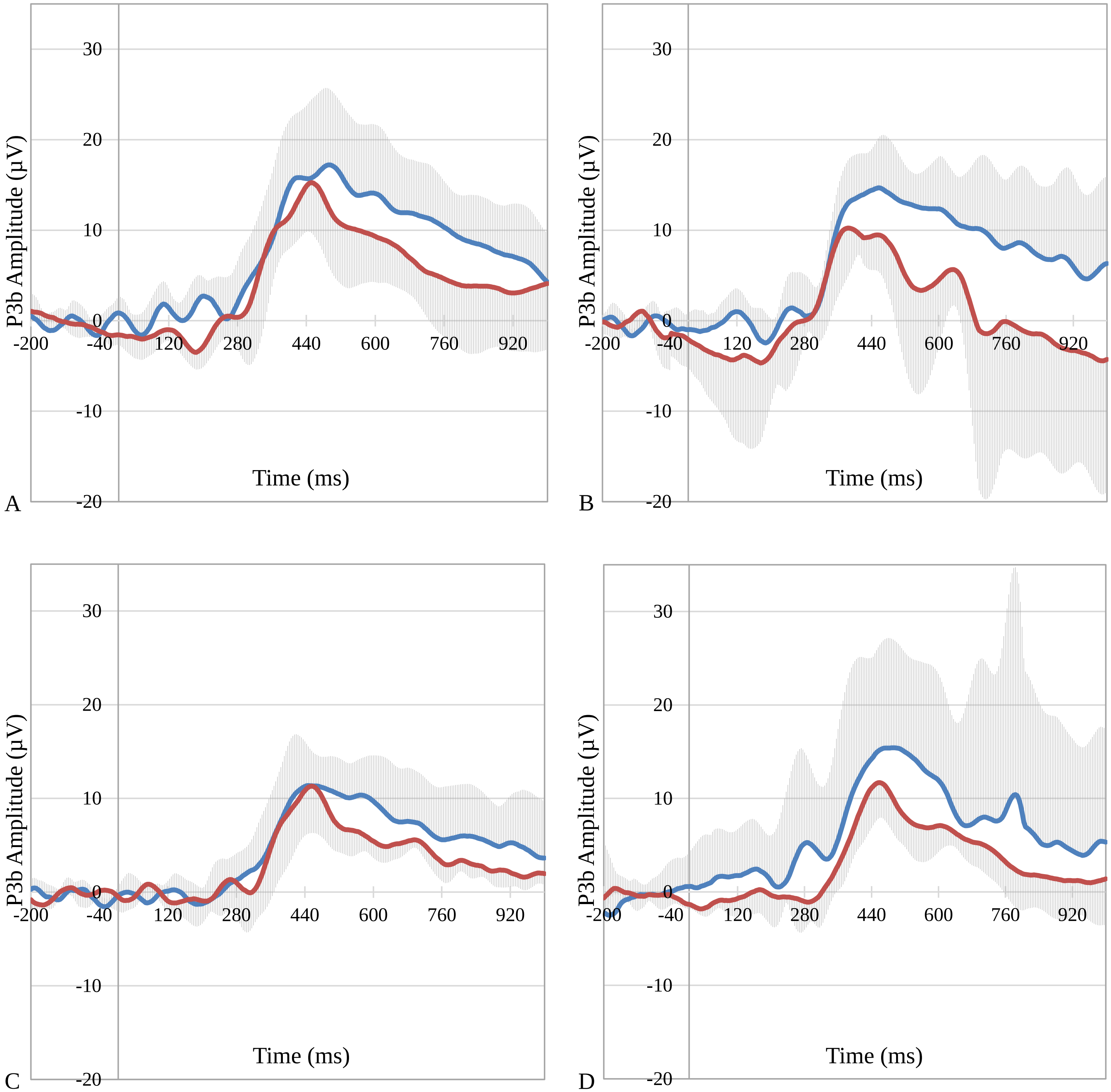

Figure 4.3 a) Baseline, b) Midseason, c) Postseason, and d) Follow-Up mean P3b amplitudes for big unskilled group. High impact group average is in red (minus 1 standard deviation) low impact is in blue (plus 1 standard deviation).

4.2 Number of Impacts Experienced by 2015 Team

The small skilled group consisted of 17 participants – nine defensive backs and eight wide receivers. Eight participants were classified as high impact players and nine as low impact players. The small skilled group received a total of 2014 impacts to the head at midseason with an average of 118.47 ± 63.84 impacts per player. By the end of the season, small skilled players had amassed 3626 impacts with an average of 213.29 ± 110.70 impacts per player.

The big skilled group consisted of 15 participants – eight linebackers and seven running backs. Seven participants were classified as high impact players and eight as low impact players. The big skilled group received a total of 2408 impacts at midseason with an average of 160.53 ± 73.00 impacts per player. By the end of the season, players in the big skilled group had amassed 4270 impacts with an average of 284.67 ± 141.58 impacts per player.

The big unskilled group consisted of 13 participants – five defensive linemen and eight offensive linemen. Six participants were classified as high impact players and seven as low impact players. The big unskilled group received a total of 4138 impacts to the head at midseason with an average of 318.31 ± 202.18 impacts per player. By the end of the season, big unskilled players had amassed 7,210 impacts with an average of 554.62 ± 303.01 impacts per player.

The whole team received a total of 8,560 impacts to the head at midseason with an average of 190.22 ± 146.50 impacts per player. By the end of the season, the team had amassed 15,106 impacts with an average of 335.69 ± 238.14 impacts per player. (Tables of cumulative impacts are reported in the Appendix).

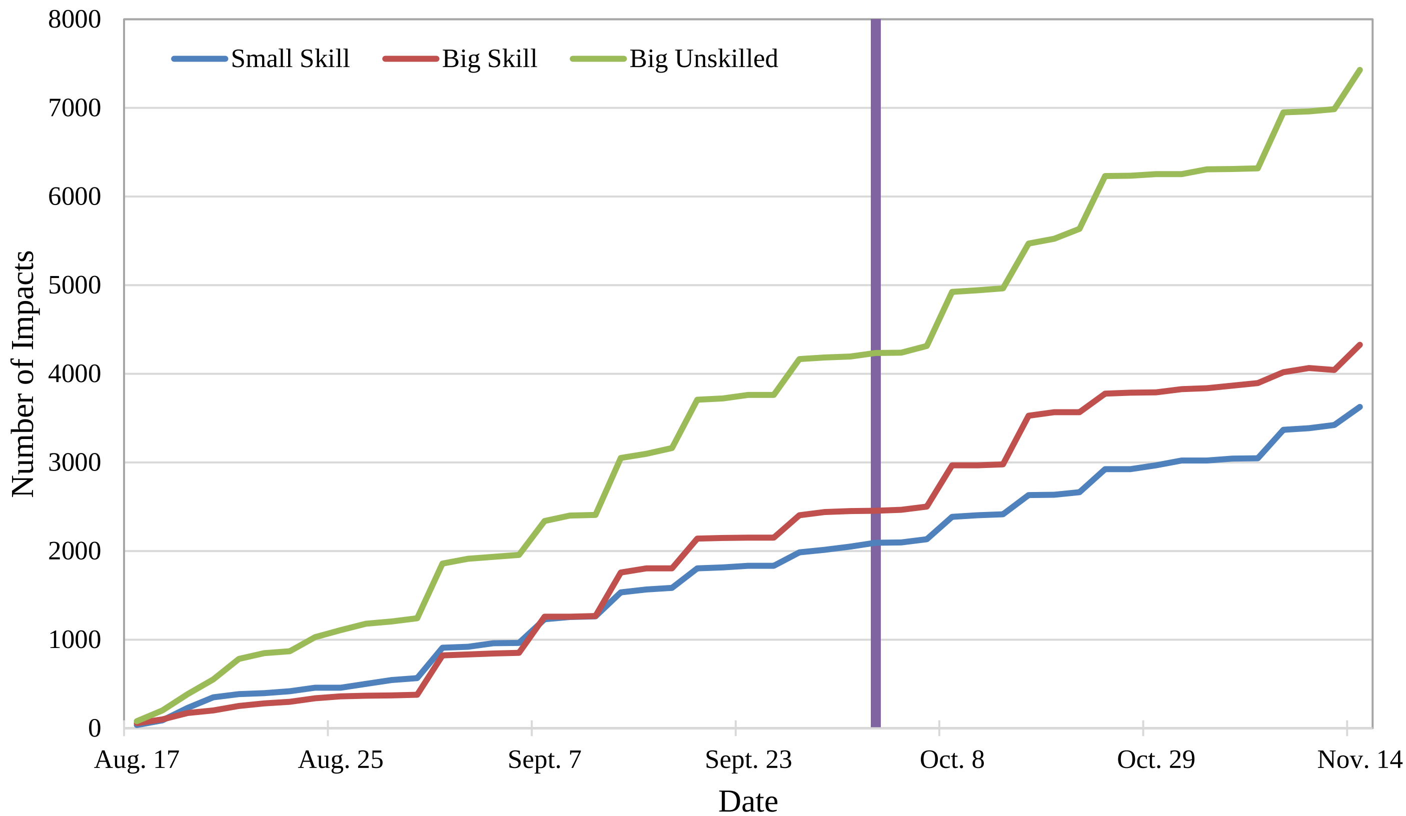

Figure 4.4 Cumulative impacts by group during the 2015 season. The vertical purple line denotes midseason.

4.3 Athlete Exposure Events

The midseason was comprised of a high intensity training camp with five games afterwards. In total, the athletes participated in 23 full practices (± 2 depending when their midseason neurophysiological test was completed), four shell practices, seven helmet practices, and five games over 46 days.

In contrast, the remainder of the season was comprised of 13 full practices, one shell practice, five helmet practices, and five games over 44 days.

Table 4.1: Number of athlete exposure events from baseline to midseason and midseason to postseason neurophysiological test periods.

	Baseline - Midseason	Midseason - Postseason
Full Pads Practice	23	13
Helmet Practice	7	5
Shell Practice	4	1
Games (playoff)	5	3 (2)
Length (days)	46	44

Table 4.2: The average and standard deviation for P3b amplitudes (μV) in each skill group across all four testing points.

	Baseline		Midseason		Postseason		Follow-up	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Small Skilled	19.64	8.68	16.78	9.23	13.82	4.82	14.02	6.02
Big Skilled	18.05	6.63	17.29	5.55	15.81	5.55	13.47	5.86
Big Unskilled	17.98	7.03	16.29	4.44	13.38	4.44	15.57	7.72
Total	**18.63**	**7.45**	**16.81**	**7.15**	**14.36**	**4.97**	**14.29**	**6.41**

Baseline measures of P3b amplitudes were not significantly different between groups ($p>0.05$).

5 Discussion

The purpose of this thesis was to determine whether Canadian university football players undergo changes in cognitive functioning based on the number of subconcussive impacts that they receive throughout a season of play. P3b amplitude, a component of event related potentials that represents the amount of attentional resources allocated to a task, information processing, and working memory[76, 106, 122], elements that reflect cognitive function. Head impacts were measured in 45 players during games and practices for the 2015 CIS football season. The players were divided into three different skill groups, and classified as high or low based on number of head impacts in each group. It was hypothesized that players that experience a higher number of head impacts will have greater changes in their P3b amplitudes than players that experience a lower number of impacts. Statistically significant decreases in P3b amplitude compared to baseline were observed at midseason in two of the player skill groups with high number of head impacts; these changes reflected decreased amount of attentional resources allocated to a task in the high hit groups. The same player skill groups also showed significant decreases at the postseason time point, and all three groups were not significantly different than baseline at the follow-up time point.

5.1 Change in P3b amplitudes over the course of the season

Both the small skilled and big skilled groups exhibited a statistically significant decrease in P3b amplitude in high impact players compared to low impact players at midseason. These decreases did not remain at the follow-up time point. The changes observed at the midseason point likely reflect the disproportionally large number of head impacts that the players experienced in the first half of season. Although the number of games and the duration of the two periods were quite similar, there were differences in the number of head impacts. For example, the big skilled players amassed 546 more impacts in the first half of the season compared to the second half of the season while small skilled players amassed 402 more impacts between the two test points. One study has reported significant differences in the number of impacts received during games, helmet-only practices, shell practices, and full-pad practices[113]. These findings are consistent with the current study's marked increase in number of impacts over the first half of the season in the current study. Players are relatively healthy and strong during the first weeks of the regular season. Accordingly, they can sustain higher intensity practices that will include more contact, consistent with the above study's conclusion that the level of protective equipment is generally a good proxy measure for the intensity of a practice. Interestingly, at midseason and postseason the big unskilled players had almost as many head impacts as the other two skill groups combined, yet did not exhibit any significant changes in P3b amplitudes. The P3b changes were quite variable in this skill group, which could contribute to this nonsignificant finding. In a previous study on the same team during a previous season, it was found that offensive linemen had significantly lower magnitude impacts than offensive back and wide receiver positions[18]. In the current study, the big unskilled group is 61.5% composed of offensive linemen. The small skilled group includes wide receivers and big skilled group includes offensive backs (runningbacks, quarterbacks, and fullbacks). Taken together, the big unskilled players may experience a larger number of impacts, but these impacts are smaller in magnitude than those experienced by the other skill groups. It appears that these types of head impact exposure do not lead to decreases in P3b amplitude.

P3b amplitude also showed a statistically significant decrease in the small skilled and big skilled high impact players compared to the low impact players at the end of the season Although the team totaled less impacts in the second half of the season compared to the first, the high impact players continued to show decreased P3b amplitudes relative to baseline. This decrease in total impacts can be explained by the team's coaching philosophy. The coaching philosophy for this team was to reduce the amount of contact in practices each week leading up to games. In addition, the coaching directive stated that small skilled players should refrain from taking part in contact during the majority of practice to avoid injury. In contrast, the coaching directive stated that big skilled and big unskilled players continue to endure contact to maintain proper tackling and blocking techniques (with the exception of quarterbacks). This occurred during a controlled and structured twenty-minute period of practice, which was at a decreased exposure than the first half of the season. Coaching philosophies on contact differ between coaches[23]. The coaching directive of this team is consistent with the overarching goal of reducing head impact exposures by reducing the number of contact practices, as identified by previous studies[23, 113]. To further protect the brains of football players, proper tackling and blocking techniques should be utilized at all times in practice. Removing the head as a tool used in the tackling progression could greatly reduce the head impact exposure. Coaches can also use tackling dummies and bags during practice for players to practice on, rather than teammates. As with most skills, if tackling is taught properly in a controlled setting, it should translate to games where the style of play is less controlled.

P3b amplitude did not show a statistically significant change from baseline in any skill groups at the follow-up time point. Three out of the six impact frequency groups exhibited an increase in change in P3b amplitude relative to baseline. This illustrates that the changes in cognitive function that occur during the football season appear to recover in the offseason.

The P3b amplitudes in the current study were comparable to previous studies in football players. For example, first year high school athletes' mean P3b amplitude was 12.35 μV while the upper year athletes' was 8.83 μV[145]. The mean P3b amplitude for the current study across all participants was 16.02 μV (Tables of P3b amplitudes are reported in the Appendix). These differences are the same order of magnitude, and may have occurred due to equipment differences such as the electrode and amplifier impedances. Interestingly, the study with high school athletes did not find a relationship between subconcussive impacts and brain function over the course of a season, but did find that P3b amplitudes were significantly decreased in upper year athletes compared to first year athletes.

The significant decrease in P3b amplitude at a midseason time point yields new information about subconcussive impacts. While studies have found decreased amplitudes after diagnosed concussion[13, 37, 47, 78] and between preseason and postseason testing[145], we are not aware of any studies that have reported changes during the course of the season. One research group has reported statistically significant differences in changes relative to baseline on visual memory scores in a cognitive test one month into the football season[107]. This is consistent with impaired efficiency of working memory tasks, similar to deficits in P3b amplitude. In separate papers, this research group also reports significant metabolic deviations from impact exposure[108], and between football players at baseline and noncontact sport controls[107], indicating underlying biochemical changes consequential to subconcussive impacts.

Numerous studies have found a decrease in P3b amplitude in concussed athletes compared to non-concussed athletes[13, 37, 47, 78]. The reduction in P3 amplitude observed in these studies represents a reduced amount of attention resources allocated to the task. The changes in P3b appear to be related to the number of head injuries. For example, one study compared athletes with multiple concussions to those with single concussions and a control group; they observed that the P3b wave was significantly reduced in the group of athletes with multiple concussions compared to those with single concussions and the control group[30]. This idea that accumulated concussions lead to increased impairments is echoed in several studies. One study has reported changes in brain metabolism that are proportional to the number of accumulated head impacts within the football season[108]. Also, the study that compared first year football players to upper year players, identified that the accumulation of subconcussive impacts over multiple seasons might explain the differences in P3b amplitude between the two groups. The current study supports these findings, as all participants of this study had played at least one year of university football. Thus, it is possible that the athletes' subconcussive histories are accumulating each season and are reflected in attenuated P3b amplitudes.

A study on high school football players measured number of impacts to the head and neurophysiologic function with fMRI[124]. A subset of players in this study were never clinically diagnosed with a concussion but performed similarly to individuals who were clinically diagnosed with a concussion. This seems to indicate that there are functional neurophysiologic consequences to repeated head impacts, even in players that are not diagnosed with a concussion. Similarly, significant relationships between the number of head impacts and ensuing neurophysiological change were found in high school football players over two seasons[8].

5.2 Limitations

One limitation of this study was the length of the season. For the current study, the regular season only consisted of eight games with an additional two playoff games. However, the average NCAA football season is twelve games. The majority of published studies followed NCAA teams where the season length is longer. Future studies should normalize results to per practice or per athletic exposure so teams of varying schedule length can be compared.

In relation to other studies[37, 124, 145], the current study had a very large sample size. However, more players will be needed in order to make further comparisons of P3b amplitudes between positions, or to investigate thresholds that are leading to neurophysiologic consequences. Future work could include a comparison between players who participate in practices and play in games, and those who only participate in practice.

Another limitation was the timing of the neurophysiological tests. The midseason assessment yielded important information regarding cumulative impact exposure, but more frequent testing would further clarify this important relationship. In addition, baseline neurophysiological test before the following season would also reveal whether the player fully returned to their previous baseline values over the offseason or whether there is some sort of accumulation season over season as reported in one study[145].

Another limitation of the current study is that there was no control group. A comparison between noncontact sport athletes and football players would determine if a football player's baseline measure is a true baseline in comparison to healthy young males of the same demographic that are not exposed to repetitive subconcussive impacts. In addition, this comparison could control for potential changes in cognitive function due to the fact that the football players are also engaged in full-time academic studies.

This study evaluated P3b in response to a visual oddball paradigm stimulus. Another study found that an auditory oddball paradigm with simple visual distracter improves sensitivity to cognitive deficits[144]. As well, the current study exclusively focused on the amplitude of the P3b wave. P3b latency and P3a waves could be included in future investigations as they may offer complementary information about different aspects of cognitive function.

This study did not consider the magnitude of the impacts that the players received, just the total sum of them. The fact that we observed statistically significant changes in cognition justifies this metric for quantifying head impact exposure, but future studies should examine head impact kinematic measures such as accumulated linear and rotational accelerations to explore the underlying injury mechanisms more fully.

A recording threshold of 15 g was chosen for this study which means that we did not quantify the number of impacts below this threshold. This may not be important for this study of cognitive functioning since impacts below the 15 g threshold are considered activities of daily living and not believed to have any neurological consequence[73].

6 Conclusion

Results showed in the small skilled and big skilled groups that P3b amplitudes of high impact players had a greater decrease from baseline to midseason than the P3b amplitudes of low impact players. Similarly, it was found that the P3b amplitudes of high impact players had a greater decrease from baseline to postseason than the P3b amplitudes of low impact players in the small skilled and big skilled groups. These results are consistent with the hypotheses. In contrast, big unskilled players did not exhibit any significant P3b amplitude changes from baseline throughout the season, which was not consistent with the hypothesis. As was expected, and consistent with the hypothesis, all players showed a return to baseline P3b amplitude at the follow-up test.

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Appendix

Table 0.1: Sample descriptives and statistical significance for the change in P3b amplitude (μV) between baseline and midseason

	Midseason							
Group	**High Impact**		**Low Impact**		**t**	**df**	***p***	**95% Confidence Interval**
	Mean	**SD**	**Mean**	**SD**				
Small Skilled	–7.46	7.89	1.23	6.25	-2.53	15	**0.011**	[–∞,–2.68]
Big Skilled	–2.87	2.25	1.10	3.84	-2.40	13	**0.016**	[–∞,–1.04]
Big Unskilled	–0.53	7.82	–4.72	2.60	1.24	11	0.121	[–∞, 9.79]

Table 0.2: Sample descriptives and statistical significance for the change in P3b amplitude (μV) between baseline and postseason

	Postseason							
Group	**High Impact**		**Low Impact**		**t**	**df**	***p***	**95% Confidence Interval**
	Mean	**SD**	**Mean**	**SD**				
Small Skilled	–4.36	2.05	–0.19	5.51	–1.88	15	**0.041**	[–∞,–0.54]
Big Skilled	–2.27	1.74	0.27	2.19	2.33	13	**0.020**	[–∞,–0.71]
Big Unskilled	–2.80	3.21	–1.52	1.26	–0.74	11	0.238	[–∞, 1.08]

Table 0.3: Sample descriptives and statistical significance for the change in P3b amplitude (μV) between baseline and follow-up

	Follow-up							
Skill Group	**High Impact**		**Low Impact**		**t**	**df**	***p***	**95% Confidence Interval**
	Mean	**SD**	**Mean**	**SD**				
Small Skilled	0.89	3.40	–0.41	4.71	0.61	15	0.551	[–3.24, 5.83]
Big Skilled	–1.86	2.62	–2.75	7.29	0.306	13	0.306	[–5.41, 7.20]
Big Unskilled	0.40	2.35	0.88	4.75	–0.43	11	0.666	[–5.30, 4.34]

Table 0.4: The average and standard deviation of the number of impacts at midseason and postseason testing points for each skill group.

		Midseason			**Postseason**		
Group	**n**	**Total**	**Mean**	**SD**	**Total**	**Mean**	**SD**
Small Skilled	17	2014	118.47	63.84	3626	213.29	110.70
Big Skilled	15	2408	160.53	73.00	4270	284.67	141.58
Big Unskilled	13	4138	256.46	151.52	7210	554.62	303.01
Total	**45**	**8560**	**190.22**	**146.50**	**15106**	**335.69**	**238.14**

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