

Assessing the Impact of Concussion History on the N200, P300 and Reward Positivity

by

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Bachelor of Science (Cum Laude), University of Wisconsin – Stout, 2014

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ABSTRACT

Traumatic brain injuries (TBI) are one of the leading causes of disability worldwide (Zitnay, 2008), yet one of the least understood neurological conditions (Duncan, 2005). Research has examined short-term deficits; however, less focus has been on the consequences of multiple concussions. Previous electroencephalography (EEG) concussion research has examined the N200 and P300 human event-related potential (ERP) components, yielding inconclusive results (Duncan, Kosmidis & Mirsky, 2005). An ERP component not as frequently examined is the reward positivity, generated by the anterior cingulate cortex (ACC), a region which experiences increased anatomical stress following injury.

In this study, 51 students from the University of Victoria took a ‘Concussion Survey’ to determine participant history and groups; no history of concussion, a single injury or multiple injuries (2+). Participants performed an oddball and decision-making task while EEG data was collected.

No significant differences were found between groups for the N200, P300 or reward positivity peak latencies or amplitudes. Both concussion groups yielded attenuated peak amplitudes, but no differences existed between the group with a single concussion versus multiple. Unexpectedly, N200 and reward positivity peak latencies were greater in the group with single injuries, compared to those with a history of multiple concussions.

This study adds to a continuous line of inconclusive research on the N200 and P300, suggesting minimal cognitive deficits result from concussive injuries. Furthermore, no noticeable differences were observed between groups with a single versus multiple injuries. While the ACC is located in a region of increased stress following TBI, functional deficits impacting the reward positivity may not be as significant as previously hypothesized. Results may be impacted by confounding variables, including not reliably being able to account for time since injury, injury severity and differences in gender dispersion of participants. With concussions on the rise, continued research, particularly longitudinally and within-subjects is critical for the advancement of both TBI prevention and management.

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CHAPTER ONE: AN INTRODUCTION AND REVIEW

1.1 Overview

Traumatic brain injury (TBI) is one of the most common injuries and leading causes of disability worldwide (Zitnay et al., 2008). According to Brain Injury Canada, it is estimated that over a million people live with TBI, an injury with prevalence rates greater than breast cancer, spinal cord injury, multiple sclerosis and HIV/AIDS combined (Brain Injury Canada). Even with such high prevalence, TBI is arguably one of the least understood neurological conditions (Duncan, Summers, Perla, Coburn & Mirsky, 2011). In sports medicine, sport-related concussion is one of the most complex injuries to identify and manage (McCrory et al., 2017). Aside from known cognitive and behavioral impacts to the patient, the Public Health Agency of Canada cited direct costs (drug costs, hospital and physician care) of TBI at \$151.7 million. This steep value did not include complex care, continued rehabilitation, costs paid out-of-pocket or by private insurance and individuals who did not meet diagnostic screening requirements entering the hospital (Canadian Institute for Health Information, 2007). Finkelstein, Corso & Miller (2006) found that direct and indirect costs of TBI in the United States of America in 2000 were \$60 billion. These costs included direct medical expenses and considered an individual's loss of independence and 'productivity' within the workplace (Finkelstein et al., 2006; Zitnay et al., 2008). Studies examining direct versus indirect costs of TBI have found direct medical expenses are minimal in comparison to indirect costs following TBI (Finkelstein et al., 2006). While financial burdens to both patient and society are exorbitant, it is important to distinguish that costs resulting from mild TBIs and concussions are likely only a small percentage of this large value. Impacting such a significant number and wide spectrum of individuals and with no 'perfect' test to rely on for immediate diagnosis, it is no question as to why TBIs have been

coined a ‘silent epidemic’ (McCrary et al., 2017; Langlois, Marr, Mitchko & Johnson, 2005; Canadian Institute for Health Information, 2007).

Several terms are used to describe TBI. These terms are according to the type and severity of injury (i.e., closed headed injury [CHI], post-concussion syndrome [PCS], mild traumatic brain injury [mTBI] and concussion). A survey verified that 1 of 3 Americans are unacquainted with the term ‘brain injury’ and associate them with more serious injuries (Langlois et al., 2005). The terms concussion and mild traumatic brain injury (mTBI) are increasingly being referred to interchangeably (Heads Up, 2009). For these reasons, unless otherwise referred to, head injuries dealt with in the context of this report will be mild in nature and referred to as concussions.

1.2 Operational Definition

The Centers for Disease Control (CDC) cite concussion as a “complex pathophysiologic process affecting the brain, induced by traumatic biomechanical forces secondary to direct or indirect forces to the head.” Characteristically, concussion affects neurometabolic and functional processes. However, more severe brain injuries cause further disruption, typically impacting neural networks via physical and structural alterations to the brain itself (Heads Up, 2009).

Individuals stricken with a concussive injury may suffer from a variety of symptoms that span cognitive, psychological and physical deficiencies. Commonly, symptoms are associated with, but not limited to: headache, confusion, dizziness, nausea, light/noise sensitivity, an inability to focus, lack of physical coordination, postural stability, irritability, anxiety, frustration, depression, fatigue, memory and information processing deficits. The extent of these deficits is dependent on the magnitude of force, as well as the locus of injury insult (Broglio, Moore & Hillman, 2011; Duncan et al., 2005).

As discussed at the Concussion in Sport International Conference in 2016, operational definitions exist for clinical ‘recognition.’ Nevertheless, these definitions do not distinguish between injury severity nor do they give insight to impairments on a cellular level, the sequelae or persistence of symptomology which may continue (McCroory et al., 2017).

1.3 What is the Problem?

While millions of concussions occur annually, they are not limited to explicit populations. Injuries impact soldiers on the battlefield, casual civilians by way of falls, work and motor vehicle accidents (MVAs) and both recreational and professional athletes in contact and non-contact sports, alike.

1.3.1 Active Combat and Blast Injuries

As civilians are, all service members are susceptible to concussions. However, for those deployed in active combat situations, blast forces (60%) are the most common cause of head injury, mTBIs or concussions being the most common of these forces (80%). Concussions are commonly thought of as being resultant of a direct insult to the head or rotational forces. However, blast forces resulting from supersonic, acoustic waves and winds traveling through the brain yield trauma of their own. The wave motion following blast forces yield unprecedented acceleration effects to the cellular structure of neurons. (Hoffman & Harrison, 2009; McKee & Robinson, 2014). Akin to blunt force injuries, there are numerous confounding variables that may impact the severity of the head injury, including the nature of the improvised explosive device (IED), such as the distance from the explosion and whether it occurred in an open field or closed quarters. Systematic inflammatory responses to blast forces make soldiers more susceptible to psychiatric conditions. In comparison to acceleration/deceleration and impact injury models, blast injuries yield different patterns of trauma (McKee et al., 2016). The orbital

frontal cortex has shown to be significantly vulnerable due to cranial architecture, leading to potential disinhibition of regions managing both fear and anxiety (Hoffman & Harrison, 2009). Research has shown that even low-level blast injuries may cause cellular changes (McKee et al., 2016).

1.3.2. Concussion in Sport

Sports are a cultural aspect of society responsible for physical, social and psychological benefits to the participant. While recreational activities and organized sport have categorical positive effects on social, physical and mental benefits, injury is always a risk. The CDC estimated that in the United States up to 3.8 million sport-related concussions occur annually as a result of physical and recreational activities. This statistic doubled between 1997 and 2007 for athletes between 8-19 years old (Langlois, Rutland-Brown & Wald, 2006; Bahkos, Lockhart, Myers & Linakis, 2010). Whether this evolution is due to an increase in injuries or increased rates of injury reporting is up for debate. What can be said with certainty is that concussions encompassing all populations are underestimated and underreported.

While full contact, high-risk sports yield greater concussion incident rates (e.g., football, hockey), sport-related concussion can occur in various sports (Bahkos et al., 2010; Covassin, Swanik & Sachs, 2003; Marar, McIlvain, Fields & Comstock, 2012). Aside from high-risk, high-contact sports, utmost concern within sport-related concussions lies among younger athletes. During youth and adolescence, brains are in critical developmental phases and therefore, more vulnerable to impacts and resultant injury. It has been found that recovery times following a sport-related concussion were nearly double in adolescent athletes in comparison to their young adult counterparts (Field, Collins, Lovell & Maroon, 2003). Evidence shows that the brain develops regionally as children age, continuing through early adulthood. Specifically, cortical

gray matter in the occipital lobe may continue to mature until an individual reaches their twenties (Giedd et al., 1999). The continued development of the adolescent brain may justify why younger individuals are showing more susceptibility and extended recovery periods compared to adults.

1.3.3 Susceptibility of the General Population

Throughout day-to-day life, the majority of the population is not consciously thinking about the likelihood of sustaining a head injury. Blast impacts are often specific to military personnel and sport-related concussions certainly wouldn't affect a middle-aged mother who is a musician working a nine-to-five job. That being said, everyone is susceptible to head injuries whether from general accidents, such as falls, hitting one's head, MVAs or assaults. A review between 2002 and 2006 found that falls were the leading cause of concussion and highest incident rates were reserved for those younger than four and older than 65 (Faul, Xu, Wald & Coronado, 2010).

Aside from increased risks due to driving an automobile or participating in athletics, other risk factors impacting the general population have been shown. None of which can be controlled, they include age, gender, history of concussion, injury severity and psychological comorbidities (Arciniegas, 2011, Cassidy et al., 2004). In a study which examined NCAA football players, athletes with a history of three or more concussions were three times as likely to sustain another head injury and experienced longer durations of recovery (Guskiewicz et al., 2003). While participation in athletics applies to only a subset of the general population, anyone can be unfortunate enough to be victim to multiple head injuries.

Presence of TBI history is enough to yield an increased risk of suicide ideation. Particularly, individuals with a history of substance misuse and anxiety disorders are particularly

more susceptible to suicide and ideation (Tsaousides, Cantor & Gordon, 2011). A study conducted in Northern Finland found that injury severity, gender, age and presence of psychiatric disorders were all predictors for suicidal tendencies in patients with a history of brain injury. Victims who sustained a concussive brain injury were younger at the time of suicide, whereas victims who sustained a more serious brain lesion were older and carried out their suicide in a more violent manner. Patients with TBI history were more likely to have been previously treated at the hospital for either psychiatric illness or substance misuse (Mainio et al., 2007).

While not as frequently discussed in the media compared to sport-related injuries, the presence of TBI on a day to day basis is worth noting. In Canada, everyday 456 people sustain a brain injury, nearly one every three minutes (Brain Trust Canada).

1.4 Concussions Today

Despite immediate, short-term cognitive effects being well understood, there is room to grow in comprehension of long-term consequences of concussion. Studies on aging, professional athletes have suggested that concussion sequelae in the long term may include mild cognitive impairment (MCI), depression, dementia and Alzheimer's disease (Guskiewicz et al., 2005; Guskiewicz et al., 2007). Whether due to cumulative effects of multiple concussive and sub-concussive blows or lingering post concussive syndrome (PCS), the consequential effects of concussion which may emerge later in life are not as well understood.

A study following a horse jockey who sustained 10-12 concussions throughout his career found cerebral atrophy 10 years post retirement, accompanied by progressive short-term memory loss. While punch drunk syndrome and chronic traumatic encephalopathy (CTE) are associated with boxers and football players, jump jockeys are becoming a population of increasing interest due to high rates of concussive impacts in the sport (McCrory, Turner & Murray, 2004).

The increasing amount of attention concussions have gotten over the last two decades due to a surge in sport-related incidents is two-fold. A rise in head impact research and respective media coverage has increased societal awareness for not only the immediate effects, but cumulative, long-term consequences, as well. With the release of documentaries such as Steve James', *Head Games*, PBS's *Frontline: League of Denial: NFL's Concussion Crisis*, and theatrical film *Concussion*, sport-related concussions are demanding their respective attention from the public. Significant progress is being made at a rapid pace. Only a decade ago was the second diagnosed case of CTE in a NFL player discovered (Omalu et al., 2006). In 2013 results were published citing the first large subset of NFL athletes examined. Results were staggering and reinforced bold declarations of recent films. Of the brains of 94 NFL players examined post-mortem, 90 expressed histological signs of (CTE (McKee et al., 2013). CTE is a neurodegenerative disease resultant of repetitive, concussive and sub-concussive, symptomatic and asymptomatic blows to the head (McKee et al., 2009). To date, the largest study examining CTE found that 177 of 202 brains expressed cellular CTE pathology. Clinical results found that 96% of participants had a recognizable, progressive course according to informants. Of these informants, nearly half reported mood or behavior symptomology, to include substance misuse, suicidality and/or history of psychiatric illness within the family (Mez et al., 2017).

Research is continuing to pave the way, furthering understanding of behavioral and cognitive deficits following concussion, however, little emphasis has been put on the impact of long-term effects of cumulative, multiple concussions, until very recently. In 2010, Owen Thomas, a 21-year-old, collegiate football player from the University of Pennsylvania committed suicide. Autopsy reports had shown early proliferation of the same trauma induced, neural degeneration seen in NFL players with CTE. While Thomas was the youngest person known to

express pathological signs of CTE, he had never been diagnosed with a concussion. Rather, he mentioned dealing with headaches and enjoyed being the player that “hit really hard” (Schwarz, 2010).

An examination of four veterans involved in Operation Enduring Freedom and Operation Iraqi Freedom found that all four expressed CTE pathology at the time of their death (McKee & Robinson, 2014). Pathologies seen following blast impacts are extremely comparable to those found in young athletes who have sustained sports related head impacts, suggesting similar biomechanical mechanisms between blast and concussion related trauma (Goldstein et al., 2012). While we have to be critical of assuming causation and correlation between CTE, suicide and contact sports, continued findings further support to the theory that athletes, soldiers and the general populous, alike, are susceptible to the damaging effects of repetitive head impacts and the accumulation of neural degeneration.

Of great concern, injuries understood behaviorally as ‘mild,’ are proving to be more severe on a cellular level. In 2004, Bigler produced a case report on a 47-year-old man who sustained a mild concussion in a car accident. On neuropsychological tests, the man tested normally (aside from minor short-term memory and processing speed deficits). Seven months later, the man passed away from unrelated circumstances. Interestingly, his autopsy expressed micro hemorrhagic lesions that were not previously detected by CT or SPECT scans. Bigler’s case report supports current theory that even the most mild head injuries may cause neural degeneration not previously anticipated. While there are a handful of neurocognitive assessments and imaging techniques in place, the fact that Bigler’s participant tested normally on neuropsychological exams suggests the reliability of these measures may not be the most ideal at determining more micro level deficits (Bigler, 2004).

Currently, the greatest struggle facing concussion management is accurate and efficient identification of injury, to include societal education and outreach of symptomology and potential consequences. For example, a study examining youth boys rugby, surveyed players on why they wore headgear and their feelings towards it. Primarily, preventative safety measures were the sole influence as to why players would wear headgear. However, this was coupled with an increase in confidence and a feeling of being able to take on harder tackles (Finch, McIntosh & McCrory, 2001). Research such as this suggests that efforts need to be made to continue to educate individuals of a false sense of security which may lead to more severe injuries.

There are a handful of clinical examinations which exist to identify concussion, including subjective patient reports, neurocognitive battery tests (NBT) and various neuroimaging methods. Unfortunately, comprehensive concussion recognition/diagnosis is extremely elusive for medical professionals, clinicians and researchers alike due to the heterogeneity of concussion definitions and symptomology. The nature of concussions is as elusive as it is ‘invisible,’ observable injury need not be present for cognitive deficits to manifest.

1.5 What is a Concussion?

According to Heads Up, an initiative by the Centers for Disease Control and Prevention a concussion is a “complex pathophysiological process affecting the brain, induced by traumatic or biomechanical forces secondary to direct or indirect forces to the head” (Heads Up, 2009). Concussions are a unique medical condition, similar to fingerprints; no two are alike. Depending on various confounding factors and injury severity, neural networks via physical or structural alterations may occur (Gennarelli & Graham, 1998). Injury severity is dependent on causal (and individual) factors, including, but not limited to: method of sustained injury, via blast, acceleration/deceleration, blunt impact, mechanical forces, number of previous head injuries, the

individual's age, neurogenetics of repair, neuroplasticity and neurotransmitter function (Arciniegas, 2011). Physical disability or even death may result from more severe concussions, however, the most common effects include a span of physiological, psychological and cognitive symptoms. These symptoms will vary person to person and range from a few hours, weeks, years or for the very unfortunate, permanently.

There is no question that head impacts can result in cognitive deficits, however, symptoms vary greatly in degree and duration. Loss of consciousness (LOC) is a definitive symptom of TBI. Duration and depth of LOC has been proposed as one of the most effective methods in attempting to predict concussion severity (Alexander et al., 1995). However, LOC is not necessary for individuals to sustain a concussion and experience life altering symptoms (Kelly and Rosenberg, 1997) which may include disruption of executive functioning (Demery et al., 2010), learning, memory (Watt, Shores & Kinoshita, 1999), slowed processing speeds (Spikman, Timmerman, van Zomeren & Deelman, 1999) and difficulty planning, initiating and executing tasks (Stuss & Gow, 1992).

1.5.1 Mechanisms

Fundamental mechanism of concussion results from rapid acceleration/deceleration forces on brain tissue, resulting in stretching and shearing of neurons. While one would assume the type of impact is the strongest predictor to injury severity, the physics of impact, both force and direction are most critical to cellular sequelae (Ommaya & Gennarelli, 1974).

Symptoms of concussion may result from primary incident and/or the secondary reaction. Primary injuries are specific to time of injury, when diffuse axonal injury (DAI) or onset of hemorrhaging may occur. Secondary injuries, however, are those that develop in subsequent hours, days and weeks following initial trauma. These injuries result from a cascade of cellular,

biochemical events that result in neuronal degeneration, herniation and swelling of brain tissue (Kim & Gean, 2011; Gennarelli & Graham, 1998).

Furthermore, classification of concussive injury (and resultant symptoms) are designated according to the type of physical injury, focal and/or diffuse. A brief lesson in brain and skull anatomy will complement further understanding these types of trauma. Comparable to athletes, workers and soldiers having a false sense of protection and security with helmets, humans have a similar sense of protection knowing their brain is surrounded by a hard, seemingly impenetrable skull. Day-to-day, the rigid, bony structure of the skull provides adequate protection for the brain. In the skull cavity, the brain, which is gelatinous in form, malleable and soft, is suspended in cerebral spinal fluid. While the skull provides protection from external threats that could puncture the brain, the interior cavity does little to protecting delicate brain tissue. Various processes protrude into the skull cavity. As the brain moves within the cerebrospinal fluid (CSF) following impact, not only may it come into contact with the skull, it may impact one of these sharp processes causing lacerations and contusions to delicate brain tissue. The main example of this is the sphenoidal ridge, a process which commonly causes injury to the frontal and temporal regions of the brain (Ommaya & Gennarelli, 1974).

Focal brain injuries are localized to specific regions of the brain, but not necessarily to explicit brain function. Falls, impacts, hemorrhages, clots or lesions restricting blood flow to localized regions of the brain are all examples which may result in focal injuries. Generally, blunt force and acceleration/deceleration injuries cause focal injuries to the frontal and temporal lobes, due to the sphenoid ridge causing localized lesions (Ommaya & Gennarelli, 1974). These injuries are likely those seen on CT and MRI scans due to their hemorrhaging nature.

Diffuse axonal injuries (DAI) on the other hand typically cannot be seen on CT scans.

Only 5-10% of the most acute injuries will appear distinguishable and will generally be observed as subcortical lesions near the corpus callosum, white matter or intraventricular hemorrhages. Often the most associated influence of a DAI injury is an altered state of consciousness, with recoveries occurring over a longer term of 2-5 years (Khan, Baguley & Cameron, 2003).

It is important to understand that while focal and diffuse injuries differ, and injuries result from primary impact and/or a secondary cascade of events, concussions are far from controlled. Not only is every person unique in their physiological makeup and reaction to injury, every incidence is unique and dependent on a variety of factors, including those of impact. It has been said that while axonal injury is an encompassing factor of concussion, injuries are best related to a spectrum of events (Gennarelli & Graham, 1998).

1.5.2 Cellular Components

Critical to the comprehension of concussion is recognition that trauma and degeneration imposed on neurons is not contained to the single event at time of injury, rather a consequential process. A traumatic blow to the head occurs in an instance, but the nature of cellular damage (and therefore cognitive deficits) are both continuous and progressive, continuing to develop over subsequent hours, days and even weeks (Gennarelli & Graham, 1998; Kim & Gean, 2011).

Various hypotheses behind the process of cellular degeneration, post-concussion, exist. The most common theory focuses on acceleration/deceleration injury and degradation of the axon, mechanical strains found to be the primary component to axonal injury (Bain, Raghupathi & Meaney, 2001). Strich's work supported the idea that these forces within the cranium cause stretching and shearing of neurons result in axonal swelling (primary and secondary axotomy) (Strich, 1956; Strich 1961). Primary axotomy includes the shearing of axons comparable to

primary impact, whereas, secondary axotomy is the resultant degeneration of axons hours, days and weeks post injury (Maxwell, Watt, Graham & Gennarelli, 1993).

1.5.3 Time Components

Various immunohistochemistry markers have been utilized to determine the extent and specific time points of injury on neuronal axons. These methods are able to identify axonal changes within minutes post injury and continue examination in following hours and days. Minutes post injury, with no noticeable damage to the cell membrane of the axon (axolemma), mitochondrial swelling is detected to include an increase in neurofilament density (Maxwell, Kansatra, Graham, Adams & Gennarelli, 1988; Pettus, Christman, Giebel & Povlishock, 1994). Wait another 30 minutes and Pettus examined axonal swelling, a disarray of neurofilaments and misalignment of the axon to the axolemma (1994). Fast forward to an hour post injury and aggregations of various organelles can be found within the swollen axons, even whilst the axolemma is still intact. Swelling continues as organelles continue to accumulate. The progression of axonal pathology is gradual, yet substantial. Passing hours and days yield greater cellular disruption including both small and larger caliber axons (Stone, Walker & Povlishock, 1999). Contrary to the popular theory of shearing, even low-impact mechanical brain injury has been found to yield axonal modification (Povlishock, Erb & Astruc, 1992)

As biologists are aware, it is critical that every human physiological process maintains homeostasis. With the loss of homeostasis comes impaired, if not total loss of function. There is no doubt excess Ca^{2+} results in toxicity within the cell. Excess cytosolic Ca^{2+} in neurons activates catabolic enzymes, phospholipases and protein kinase C. Consequentially, neuronal structural proteins are degraded, the cellular membrane is broken down, oxygen free radicals are produced and an increase in Ca^{2+} influx initiates neurotoxicity via glutamate release (Choi,

1988).

Neurofilament damage is dependent on the severity of force applied to the cell. More mild concussions for example, are associated with misalignment of the cytoskeleton, whereas severe injuries cause rapid neurofilament compacting (Povlishock, Marmarou, McIntosh, Trojanowski & Moroi, 1997).

1.6 Current Diagnostic Methods

There are a handful of methods utilized for concussion recognition and diagnosis, including neurobehavioral tests (NBT), motor and balance testing and a variety of neuroimaging techniques. Abbreviated measures of concussion screening are becoming increasingly utilized for sport-related injuries, however, are not suited to be conducted in place of a neurological examination. Abbreviated methods at the time of injury are to be used for diagnosis of a suspected injury. The most beneficial approach to concussion recognition and diagnosis is through multidimensional, guided examinations (McCrory et al., 2017). A combination of neurocognitive examinations and either a CT or MRI scan are predominant detection methods. While CT scans are a bit more attainable, requiring less time and expense than an MRI, both are limited to recognizing more acute concussions, which are not the most common (Bazarian, Blyth & Cimpello, 2006). CT and MRI scans are beneficial for diagnosing severe intracranial hemorrhages and contusions requiring surgery, yet often overlook the most common, mild and diffuse injuries as being 'normal' (Gandy, Snow, Zimmerman & Deck, 1984). Diffusion tensor imaging (DTI) is a special form of MRI showing promise in distinguishing differences following head injury, focusing on injuries to white matter tracts (Arfanakis et al., 2002). Electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) are not as familiar to the general population since they aren't go-to methods of imaging in a hospital

setting. While these methods have proven to be the most sensitive in imaging, proving readily available, cost effective and beneficial in differentiating deficits in real-time cognitive function (Gosselin et al., 2010).

Like imaging, clinical and behavioral examinations are limited due to an encompassing focus being on identifying large scale cognitive and behavioral deficits. Therefore, deficits observed in clinical and behavioral exams are often associated with only acute injuries. Current scales for concussion recognition lack detection of more subtle and consistent deviations: those which are commonly associated with the majority of concussions (Broglio, Ferrara, Piland & Anderson, 2006). For individuals who have sustained more mild concussions, conventional neuropsychological examination results often fall within 'normal' limits. Consequentially, 'normal' lends to release from hospital care and an understanding that the patient is 'fine,' even though they may still be symptomatic (Bigler & Brooks, 2009).

Furthermore, several concussion recognition methods rely on self-reported measures from the injured individual, the reliability of which is becoming increasingly questioned. Aside from uncertainty of which symptoms are 'severe' enough for an individual to report, a study by McCrea and colleagues found that for unknown reasons, more than 50% of high school athletes did not report their symptoms to a coach, trainer or authority figure following receiving a concussion (McCrea, Hammeke, Olsen, Leo & Guskiewicz, 2011). Similar to McCrea, a study examining athletes previously diagnosed with concussion expressed discrepancies between self-report, neurocognitive examinations and recorded symptoms. Of the participants, 38% whom had been previously diagnosed with a concussion were cleared by their physician, even though they still expressed deficits in neurocognitive measures (Broglio, Macciocchi & Ferrara, 2007). A case study of a 50-year-old soldier who had sustained multiple injuries following blast forces

expressed normal neurocognitive examinations three months following her injuries, however, headache, nausea and eye twitching remained. Only did DTI express lingering deficits to cerebellar pathways, particularly on the left side of her brain, the side the main explosion occurred on (Warden et al., 2009).

These findings suggest a discrepancy between concussion recognition by physicians, trainers and medical professionals and the actual symptoms patients are experiencing. Whether individuals are not appropriately identifying their shortcomings, not yielding full disclosure to clinicians or simply are not aware of neurocognitive deficits, one of the greatest challenges is relying on subjective criteria received from patients. There is necessity not only on the field or on the sidelines, but in the emergency room for a more consistent and reliable method (to include previously existing testing batteries) to recognize neurocognitive effects of concussion. Only with more reliable tools will we be able to appropriately treat and mediate these concussive injuries as they occur (Broglia et al., 2007).

1.6.1 Neurocognitive Examinations

The Glasgow Coma Scale (GCS) is one of the most well-known methods clinicians use in medical settings to diagnose any acquired brain injury by examining a patient's consciousness level. Scores range between 3-15 points according to a patient's ease of motor response, comprehensible verbal expression and spontaneous opening of their eyes (Teasdale & Jennett, 1974). Effectively responding to each of these three factions, a patient theoretically could receive a score of 15 and be discharged from the hospital. However, it is not uncommon that a patient may have a passing score with a mild head injury and still be suffering from underlying cognitive deficits/symptoms not visible to clinicians. Symptoms resulting from concussions are unique to other conditions, in that sequelae of cellular damage is progressive, and therefore, functional

deficits can take hours, if not days to develop. A patient going to the hospital immediately post-injury may not display the extensiveness of their deficits.

A significant issue with the GCS lies with identifying injury according to three 'factors' of consciousness (Teasdale & Jennett, 1978) not providing substantial sustenance to the extent of potential neuronal damage. Blumbergs and colleagues looked at five patients who had received a concussion. Although no neurobehavioral data was recorded, all patients experienced a transient loss of consciousness and scored between 13-15 on the GCS. While GCS scores suggested a mild injury, in staining and examining brain tissue post-mortem (deaths unrelated to concussion), all five patients were found to have both macroscopic and microscopic, axonal injuries (Blumbergs et al., 1994). Blumberg's study suggests that while the GCS identifies levels of consciousness, it does not necessarily express the extent of damage received and suggests mild concussions may yield greater neuronal damage than previously expected.

In sport related settings, the Immediate Post Concussion Assessment Tool (ImPACT) is the most widely used neurocognitive exam following a head injury. An athlete's symptomology, visual and verbal memory, reaction time and visual motor processing speeds are measured during the task. Results from these measures yield an immediate composite score and report. The comparison of baseline and post-injury scores is intended to lighten the burden trainers and medical professionals face when formulating a return-to-play protocol. Individuals take a baseline assessment prior to their season and if a head injury occurs, a post-injury assessment will be taken, and scores compared to the individual's baseline. Issue arises if the individual has not taken a baseline or the baseline is out of date (baselines should be taken at the beginning of every season, or every year). A review by Alsalaheen and colleagues found that athletes when compared to 'normative values' were misclassified (2016).

ImPACT has strong validity, however, responsiveness, discriminant, criterion related and diagnostic accuracy validities have yet to be appropriately assessed. Furthermore, composite scores have shown to be impacted by a lack of sleep, high levels of physical exertion, testing environments (solo vs. group settings) and efforts to sandbag score results (Alsalaheen, Stockdale, Pechumer & Broglio, 2016). Development of the ImPACT resulted from attempting to alleviate practice effects which result from traditional pen and paper testing by referencing personal baseline scores, normative values and predetermined cutoffs. However, a study examining the benefit of these values found that at greatest, 35% of participants were able to sandbag their scores (Alsalaheen et al., 2016). The justification of sandbagging scores often relates to an individual attempting to get a low score on their baseline, with the idea that if they sustain an injury, they will be more likely to ‘pass’ their post-injury ImPACT assessment and return to play sooner. Even with questions of validity, the ImPACT is still one of the most utilized methods for head injury recognition and return-to-play protocol.

The Balance Error Scoring System (BESS) is another standard practice in attempting to identify concussions. Widely accepted, the examination looks at a subject’s postural stability in three different positions. Subjects are scored by their errors according to an objective list. However, as with a lot of concussion examinations, discrepancies are commonly found between inter and intra rater reliability. Finnoff and colleagues found that while some subcategories to the BESS are sufficient in reliability, the total BESS score and numerous subcategories cannot be supported as an adequate evaluation of postural stability post-concussion (Finnoff, Peterson, Hollman & Smith, 2008).

1.6.2 Neuroimaging Methods

The most familiar imaging techniques people consider with head injuries include both CT

and MRI scans, but few are aware of what these imaging techniques examine and how they differ. Computer topography (CT) scans are the most widely utilized scans in clinical settings, post-injury. The benefit of CT is a scan that takes only minutes for nearly immediate recognition of intracranial bleeding, recognition which is critical if surgery is necessary. However, the extent of neuronal damage can often be underestimated, bone may cause artifacts and potential movement yields unrefined images, making soft tissue, structural damage difficult to recognize. Resultantly, CT scans have been one of the critical components triggering biased views on concussion culture and injury severity. Patients with negative or ‘normal’ scans are often dismissed as not having sustained a brain injury, questioning the integrity of individuals who suffer[ed] from TBI (Bazarian et al., 2006). Even worse, once a negative CT scan is received, in some countries insurance fails to compensate individuals for further investigation or an MRI scan (Kim et al., 2013).

Magnetic resonance imaging (MRI), in comparison to CT is more sensitive spatially, showing greater contrast between white and gray matter, as well as axonal injury via lesions. However, distinguishing the difference between lesions and unknown objects in control scans is not as consistent. Functional magnetic resonance imaging (fMRI), detects brain abnormalities through imaging functional processes. Taken while a patient partakes in a cognitive test, fMRI detects oxygenation levels and blood flow in the brain. Areas demanding more blood flow correlate as regions with greater activity. Characteristically individuals who have sustained injury will show less activation compared to controls (Sanchez-Carrion et al., 2008). Positron emission tomography (PET) and single photon emission computer tomography (SPECT) are similar in that they rely on the injection of radioactive elements for imaging. SPECT scans,

however, measure regional cerebral blood flow (rCBF), while PET scans are more versatile, detecting blood flow, oxygen levels and cerebral, glucose metabolism (Bazarian et al., 2006). following injury, changes in white matter have been seen years following an injury and have shown correlations between injury severity and decreased white matter (Kraus et al., 2007). The downfall to DTI is being a relatively recent technology and a lack of spatial sensitivity, limiting clinicians and researchers from being able to directly know the directionality of tracts.

Imaging Techniques	How does it work?	Benefits	Challenges
Magnetic Resonance Imaging (MRI)	<ul style="list-style-type: none"> Magnet aligns protons within water molecules to generate contrast images 	<ul style="list-style-type: none"> More accurate soft tissue detection than CT scanning Non-invasive, no radiation 	<ul style="list-style-type: none"> Spatial resolution Sensitive to motion
Diffusion Tensor Imaging (DTI)	<ul style="list-style-type: none"> MR technique Based on diffusion of water molecules in tissues 	<ul style="list-style-type: none"> Shows tissue architecture Can reveal differences in white matter (tracts) Non-invasive, no radiation 	<ul style="list-style-type: none"> Spatial resolution Limited knowledge of tract directionality Sensitive to motion
Computed Tomography (CT)	<ul style="list-style-type: none"> Ionizing radiation collects 2D x-rays which can be stacked for 3D rendering 	<ul style="list-style-type: none"> More detail than conventional x-ray Ideal for imaging dense structures 	<ul style="list-style-type: none"> Difficulty imaging soft tissue
Single emission photon computed tomography (SPECT)	<ul style="list-style-type: none"> Radioactive isotope injected, binds to region of interest and is imaged with gamma ray camera 	<ul style="list-style-type: none"> Merge images of SPECT and CT scans to pinpoint abnormalities Use in both structural and functional imaging 	<ul style="list-style-type: none"> Requires injection of nuclear material Time sensitive due to isotope
Electroencephalography (EEG)	<ul style="list-style-type: none"> Measures electrical signals from summation of neurons 	<ul style="list-style-type: none"> Excellent temporal resolution Inexpensive Ease of assessing cognitive function 	<ul style="list-style-type: none"> Spatial resolution is limited due to abundant neural sources
Functional magnetic resonance imaging (fMRI)	<ul style="list-style-type: none"> Shows 'activation' by measuring oxygenation levels and blood flow 	<ul style="list-style-type: none"> Assessment of cognitive function during tasks 	<ul style="list-style-type: none"> Poor temporal resolution Difficult to interpret specific brain activity

Figure 1. Common imaging techniques utilized for head injury. Includes the technology methodology, common benefits and limitations.

While these neuroimaging techniques have their benefits and several yield good spatial resolution, current methods producing desired temporal resolution are limited. It is extremely beneficial to be able to utilize current imaging techniques to recognize bleeding post-injury and perform surgery in critical time. Shortfalls exist in individuals who may demonstrate neurological deficits, when scans fail to show physical brain damage (Bazarian et al., 2006). It would be extremely beneficial to have a method in which cognitive deficits could be recognized

and addressed in the days, weeks, months and even years post-concussion. For this reason, the intention of this study is to utilize electroencephalography (EEG), a neuroimaging technique that's been around for just short of a century and is the first that expressed abnormal brain function (Luck, 2014).

1.6.3 Electroencephalography (EEG)

A non-invasive technique, EEG is a much more ethically acceptable and affordable imaging method than those previously discussed. While the spatial resolution for EEG is good, it is not comparable to more refined methods such as MRI and DTI. Locating specific areas of activation can be challenging due to abundant neural sources from multiple, cortical regions within the brain, some of which are more difficult to separate and identify than others (Luck, 2014). However, for what EEG lacks in spatial resolution, it makes up with temporal resolution. Under optimal conditions, there is less than a 1ms delay from the time brain action occurs, to when it is recorded at the scalp. Other neuroimaging measures, in comparison, may record with a delay of hundreds of milliseconds (Luck, 2014). With such excellent temporal resolution, EEG remains one of the most dynamic, and therefore, informative neuroimaging methods, allowing for more specific questions to be answered about cognitive processes, as they occur. Furthermore, while some EEG tests may require the subject to be alert and responsive through a particular task, EEG can be collected, monitored and assessed for patients whom are not responsive.

1.7 EEG as the Method

The basis of EEG is that every cognitive process and action are carried out by neurons which produce electrical activity. When neurons are aligned appropriately, summation of the electrical signal occurs, which is digitized, recorded and amplified for researchers and clinicians

to examine. While EEG recordings represent a conglomeration of mixed neural sources, they can be isolated through analysis, and may be time-locked to specific events of interest, physical or mental (Luck, 2014). Recordings time-locked to specific stimulus presentation/interaction are known as event-related potentials (ERPs). A significant benefit of ERPs is the ability to measure the brain during performance of a task, something that isn't as readily available with CT/MRI scans. ERPs represent noticeably distinct, functional patterns of activity which correlate to neuronal aggregates (Donchin, Ritter & McCallum, 1978).

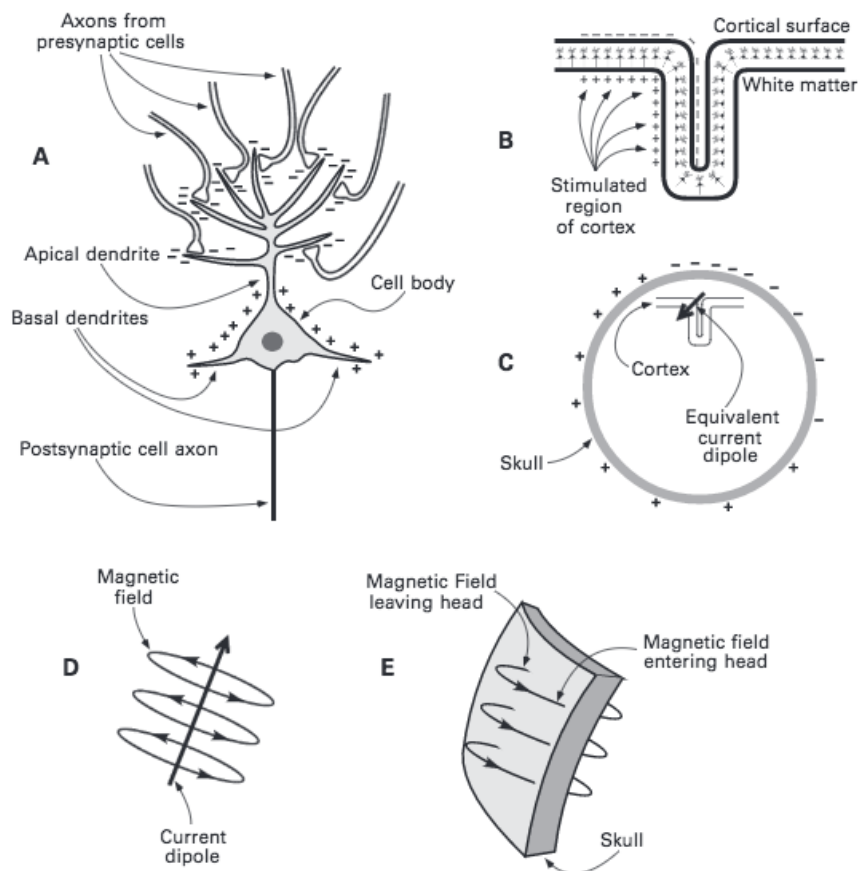


Figure 2. Principles of EEG generation. A) Individual pyramidal cells form local dipoles. B) Cortex contains hundreds of pyramidal cells which summate when stimulation occurs. C) Summation yields a single equivalent dipole. D) Sample dipole with magnetic field. E) Magnetic field as it is seen with the surface of the skull. A parallel orientation is required for recording. (Luck, 2014)

Traditionally, ERP analysis and examination revolve around ‘components.’ Components, previously, were believed to differ according to respective variances in polarity, scalp distribution and latency. While these elements are helpful in identifying components, they do not identify the individual, specific nature and principles (Luck, 2014). Components may share polarities and have temporal similarities, but have been described as belonging to ‘families. The justification behind not defining components according to solely variances in polarity, scalp distribution and latency arises from variances within these factors. Scalp distribution can vary according to the region researchers are looking at and latencies can vary within individual components (Luck, 2014).

Components are best defined as sub segments of the larger ERP waveform, representing distinct sets of voltage changes. (Woodman, 2010; Luck, 2014). Donchin and colleagues discussed components as being a source of controlled variability, their existence based on functional, systematic variations with independent and experimental variables (Donchin et al., 1978). Due to excellent temporal resolution and the ability to time-lock recordings to specific cognitive, computational actions, ERPs provide an excellent model to monitor information flow and processing within the brain.

1.7.1 Cellular Components

EEG results from a cascade of cellular electrical signaling. Action potentials are sent through single neurons, releasing neurotransmitters to a recipient cell. Once these neurotransmitters bind to the recipient cell, ion channels open or close, causing gradient changes in voltage across the cell membrane. Recording action potential voltages is extremely cumbersome, due to the anatomical reality of neurons firing at different rates. If neurons are located parallel to one another and send their signals at slightly different times, the current

simultaneously flowing through one neuron, while out of another, will terminate both signals entirely. However, if neurons send action potentials at the same time, summation of respective voltages will occur.

Consequently, electric potentials recorded from the scalp reflect change to equivalent dipoles, allowing longer durations of recordings to be taken (up to hundreds of milliseconds) and recorded from greater distances. Contrary to the challenge of action potentials being able to summate, PSPs occurring mainly from dendrites allows multiple neurons to be able to summate with one another, causing a greater electrical field and distance in which recordings can be taken (Luck, 2014). Moreover, these neurons need to be oriented in very specific anatomical positions for their potentials to summate to values great enough to be recorded (Broglia et al., 2011).

1.7.2 Examining Concussion

There are no known human EEG recordings while a head impact was sustained. Currently, only animal models allow this information to be observed by researchers. In these cases, EEG readings taken while a head impact was sustained have expressed epileptiform activity, followed by suppression and generalized slowing which lasted a few minutes before returning to normal (Shaw, 2002). Several studies have examined EEG in patients immediately following injury, to include studies examining patients weeks or even years following. While inconclusive, several reports found delayed latencies and decreased amplitudes in participants who had a history of concussion (Broglia, Pontifex, O'Connor & Hillman, 2009; Duncan et al., 2005; Polich, 2004). Gosselin and colleagues found that even athletes who were no longer symptomatic reported abnormal ERPs (2010; 2012). Current gaps in literature include longitudinal studies, in which individuals are followed sequentially through their recovery and beyond.

1.7.3 Components: N200

The N200 component is recognized by a characteristic negative deflection between 180 to 350ms following stimulus onset. Due to the presence of the N200 in a variety of conditions, the component is believed to be associated with a few different sub-components, each elicited in different regions. When the N200 is present following an auditory task with deviant stimuli, the N200 is also known as the mismatch negativity (MMN) (Näätänen, Gaillard & Mäntysalo, 1978; Näätänen, Paavilainen, Rinne & Alho, 2007).

Differences in N200 subcomponents reflect differences in processing for each task. For example, the Flanker and go/no-go tasks are common for evoking the N200 and have been found to be associated with conflict monitoring and overcoming formulaic responses in a frontocentral region. Other research which has required motor responses has found that the N200 was elicited prior to a motor response, suggesting the component to be associated with stimuli identification and distinction (Patel & Azzam, 2005). Particularly, the N200 amplitude is correlated with stimuli frequency. The less frequently stimuli occurs, the greater an increase in the N200 amplitude (Duncan-Johnson & Donchin, 1977).

The N200 has also been shown to be associated with stimuli identification, novelty detection and shifts in attention. In a review by Folstein and Van Petten, the N200 desires to be broken down into subcomponents dependent on scalp distribution of the negative deflection (2008). The focal point of evoking the N200 in this study is examining the greatest voltage differences in the posterior region of the brain, associated with odd or infrequent visual stimuli in oddball tasks.

1.7.4 Components: P300

One of the most frequented and therefore, understood ERP components is the P300 P300, first identified in 1965 by Sutton and colleagues (Sutton, Braren, Zubin, & John, 1965). Subjects were presented either an auditory click or visual flash of light to examine if differences existed between waveforms when stimuli were certain or uncertain. Of all the 36 experiments conducted, Sutton and colleagues found that when presented with an uncertain stimulus, a late, positive component that peaked around 300ms post stimulus was elicited. They continued their studies to alter the probabilities of certain to uncertain stimuli. In 22 of 29 studies, Sutton and colleagues found that the late, positive deflection was consistent. Additionally, they found that stimuli with lower probabilities (more uncertain) yielded a greater P300 amplitude (Sutton et al., 1965).

The P300 is measured according to waveform amplitude and latency (Polich, 2007). Both visual and auditory P300 are believed to be resultant of different neural generators (Duncan-Johnson, 1989). These generators will be dependent on whether examination is of the P300a or P300b. Current theory is that the P300 is sensitive to attentional resource allocation, stimulus discrimination, evaluation and categorization (Donchin & Coles, 1988; Duncan-Johnson, 1981; Patel & Azzam, 2005; Polich, 2007). When subjects were presented with target stimuli, amplitude increased from the frontal to parietal region (Johnson, 1993). Duncan and colleagues found that in studies where the task was challenging enough, ERPs yielded reduced P300 amplitudes in individuals who had sustained closed head injuries (Duncan, Kosmidis & Mirsky, 2003; Duncan et al., 2005). Furthermore, a study by Gosselin and colleagues found that depression scores following injury positively correlated with decreased P300 amplitudes in comparison to healthy counterparts (Gosselin et al., 2012).

The P300 is arguably one of the components most sensitive to overall cerebral

dysfunction (Polich, 2004). While there is quite a bit of inconclusive data on components being impacted following head injury, abnormalities exhibited in the P300 are generally more consistent, particularly with latencies. In a review by Duncan (2005), over half of the studies examined, participants expressed longer P300 latencies during visual tasks for subjects who had sustained concussion, in comparison to their healthy counterparts. The delay in P300 latencies suggests a delay in stimuli categorization and evaluation (Duncan et al., 2005). Auditory tasks in particular, yielded more delayed P300 latencies in individuals who had previously sustained concussions. Accuracy rates were comparable between healthy subjects and those who had history of concussion, however, the delayed P300 suggests higher-order auditory processes may be more susceptible to head trauma (Duncan et al., 2003). Campbell and deLugt proposed that with comparable accuracy rates, slower response times may be due to a delay of the subject double checking their response due to uncertainty (Campbell & de Lugt, 1995).

1.7.5 Components: Reward Positivity

The reward positivity is another component which will be examined in this study. The reward positivity has previously been associated with reinforcement learning and contextual sensitive material in trial and error learning tasks. Now referred to as the reward positivity, this component was previously discovered as the feedback related negativity (FRN), following an association with large phasic changes within the anterior cingulate cortex (ACC) following participants' response to positive versus negative feedback (Holroyd, Pakzed-vaezi & Krigolson, 2008; Miltner, Braun & Coles, 1997; Proudfit, 2015). The reward positivity waveform manifests as a positive deflection which is elicited at a maximum frontocentral on the scalp between 230-250 ms post-feedback. The component is the result of the difference of ERPs recorded following unanticipated rewards and in this task the difference between win versus loss feedback.

Theoretically, the reward positivity is believed to index a dopaminergic reward prediction error (RPE) signal directed to the anterior cingulate cortex (ACC) (Holroyd & Coles, 2002). Dependent on the task, the reward positivity may be associated with whether a task was completed (Holroyd, Larsen & Cohen, 2004) and how unexpected particular events are (Potts, Martin, Burton & Montague, 2006; Holroyd & Krigolson, 2007). Current theory suggests this activity is representative of reinforcement learning systems located in the medial-frontal cortex (Heydari & Holroyd, 2016; Holroyd & Coles, 2002).

Little research has been done examining the reward positivity in individuals who have sustained multiple concussions. While the ACC is associated with functional deficits following a brain injury, it's also related to an extensive neural network of the brain and which in no way could be singled out during injury. However, previous research examining traumatic brain injuries has found structural changes to the ACC a year following a single incident of concussion (Merkley et al., 2013). Not surprisingly, researchers have determined that one of the most susceptible regions of the brain, resulting from acceleration/deceleration forces, is the corpus callosum, a region responsible for integrating neural signals from one hemisphere of the brain to the other. Unfortunately, the ACC is located in the medial frontal lobe and wraps around the anterior dorsal region of the corpus callosum. This area is particularly vulnerable to head impacts due to its location near the unyielding, falx cerebri. The falx cerebri is a meningeal fold which sits between the two hemispheres of the brain, when an injury occurs, the falx cerebri acts as a fulcrum, stretching brain tissue around it (Ho, Zhou, Li & Kleiven, 2017). An increased understanding of the sensitivity of the ACC to brain trauma and a lack of in-depth studies examining the reward positivity and multiple concussions makes it a component of great interest for further study.

1.8 Proposed Study

Through two experimental tasks, I intended to examine whether individuals with a history of concussion would elicit differences in the N200, P300 and reward positivity ERP components in comparison to healthy counterparts. Furthermore, due to previous studies suggesting concussions are cumulative in nature, I sought to examine whether group differences would exist between participants who had sustained a single concussive injury in comparison to participants who had a history of multiple concussions.

It is expected that individuals with a history of concussion will have attenuated peak amplitudes and delayed latencies in comparison to healthy controls. Particularly, it is expected that during the oddball task, participants with a history of concussion will express smaller amplitudes for both the N200 and P300. Furthermore, these individuals should yield greater latencies in the N200 and P300. It is anticipated that the decision-making task will yield a reward positivity that is both delayed and yielding a smaller peak amplitude. Additionally, I expected participants with a history of multiple concussions to express greater deficits than those with a history of a single concussive injury. Results will add to a growing body of inconclusive literature examining the N200 and P300 on concussive populations and add much needed background for examining the reward positivity component.

CHAPTER TWO: METHODS

2.1 Participants

Fifty-one participants (15 males 95% CI [21.61, 25.73], 36 females 95% CI [20.00, 22.05]) from Victoria, British Columbia took part in this study; 17 having experience a single concussive incident (mean age = 20.88, 95% CI [19.30, 22.47]), 17 having experienced multiple concussive incidents, two or more concussions (mean age = 22.3, 95% CI [20.33, 24.26]) and 17 controls with no history of concussion (mean age = 22.2, 95% CI [20.51, 23.96]), whom were randomly selected for comparison. Participants were recruited via SONA System at the University of Victoria, to include word of mouth. Participation was voluntary and participants who were enrolled in respective psychology courses obtained course credit for their participation. Prior to participation in the study, informed consent was obtained in accordance with the regulations of the Human Research Ethics Board at the University of Victoria. All participants had normal or corrected-to-normal vision and no known congenital, neurological impairments. Ethical standards were upheld according to the 1964 Declaration of Helsinki.

2.2 Apparatus and Procedure

Following obtaining informed consent, participants filled out a ‘Concussion Survey,’ which included the self-report, ‘How Do You Feel Now’ symptomology chart from the SCAT-3, as well as questions screening the participants’ current medications, vision and neurological history. Questions were also asked about the participants’ concussion history, including whether a head injury had ever been sustained, and if so, whether it was formally diagnosed, time and method of injury.

Participants were seated in a sound-dampened, darkened room, in front of a 19” monitor. A four-button, colored controller and keyboard were utilized to collect responses and direct

participants through two respective tasks (an oddball and a reward based decision-making task). Tasks were written in a Matlab programming environment (version 8.4; Mathworks, Natick, Massachusetts, USA) using an extension of Psychophysics Toolbox (Brainard, 1997). EEG was recorded via a 64 channel Brain Vision ActiChamp system, according to the International 10-20 electrode configuration and a typical EEG setup (stimulus and recording machines).

2.3 Task

2.3.1 Oddball Task

The task included three brief segments of continuous EEG collection. These included a brief fixation period followed by two experimental tasks – an oddball and reward based decision-making task. The fixation period required participants to stare at a white fixation cross in the middle of a black screen to establish a baseline for each participant. Following the fixation period, participants were presented with both oddball and reward-based decision-making tasks in randomized order.

The oddball task included four blocks of 20 trials each. Visual in nature, stimuli were colored circles, either blue (MATLAB RGB value = [0 0 255]) or green (MATLAB RGB value [0 255 0]). Circles appeared individually, in the center of a dark grey monitor (MATLAB RGB value [108 108 108]) for 800 to 1200 ms. In between circle presentation a black fixation cross (MATLAB RGB value [0 0 0]) was presented for 300 to 500ms. The blue circles were the ‘odd’ stimuli (frequency 25%) and the green circles, frequent (75%). Participants were instructed to press the left button on the controller when the green circles were presented and the right button when the blue circles were presented. While frequencies remained the same, the sequence of circle color was randomized for each block and participant. Participants were not aware of how

many trials they were to undertake, nor given information about the frequency of the circles. See Figure 3.

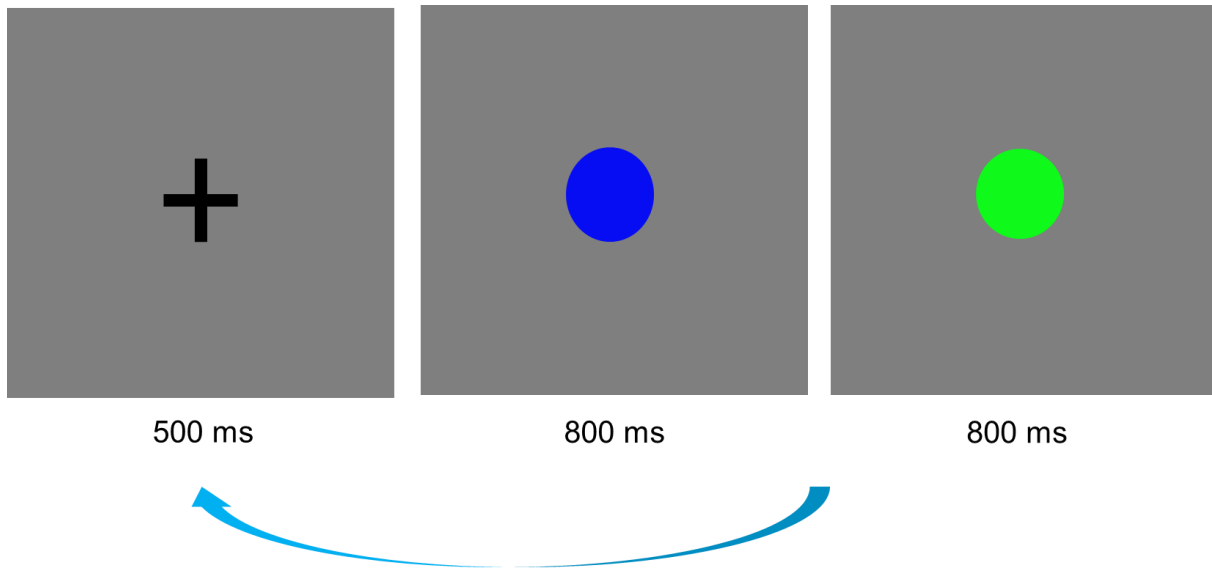


Figure 3. Visual oddball task. Participants would see a fixation cross for 500ms prior to a colored circle appearing in the center of the screen for 800ms. The circle was either blue (infrequent) or green (frequent). The participant would make a key press response correlated with the color of the circle, prior to the next circle appearing on the screen.

2.3.2 Decision Making Task

The reward based decision-making task began with participants focusing on a black fixation cross (MATLAB RGB value [0 0 0]) for 300 to 500ms. Participants were then presented with two squares, each a different color. They were then instructed to select one of the squares according to which they believed to be the ‘winning’ square. The two colors remained the same for the duration of the block, but the colored squares may have alternated whether they were presented to the left or right of each other. Following square selection, participants were presented with feedback stimuli, ‘Win’ or ‘Loss.’ One of the colors would result in more frequent rewards or ‘wins’ (60%) than the other color (10%). Location of the square, whether adjacent on the left or right side was randomized for each trial, however, the win/loss ratio of the

colors during a single block remained same. Feedback was given for 1000ms before the next trial began. The experiment included five blocks of 20 trials, each block two different colored squares would be utilized for the entirety of that block. Participants were not informed of the win/loss ratio for each color, nor were they informed of the number of trials/blocks they would participate in.

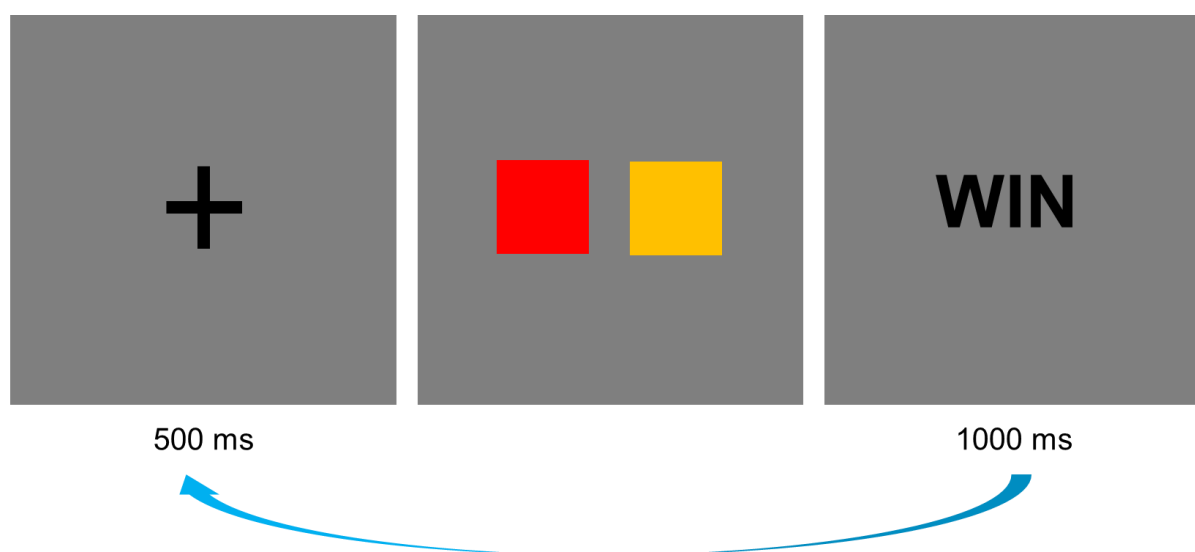


Figure 4. Decision making task utilized to elicit the reward positivity. Participants would see a fixation cross for 500ms prior to two different colored squares appearing next to each other. They then would make a selection based on which square they believed to be the square with a greater likelihood of ‘winning.’ Following square selection feedback would appear on the screen for 1000ms informing the participant if they ‘won’ or ‘lost.’

2.4 Data Analysis

EEG data was processed via BrainVision Analyzer (Version 2.1.1, Brainproducts, GmbH, Munich, Germany). Data was reviewed to remove any noisy or broken channels prior to changing the sampling rate to 250Hz (previously recorded at 1000Hz) and re-referencing the data to averaged mastoids. Supplementary, dual-pass, Butterworth filters were applied (0.1Hz to 30 Hz, Notch 60Hz). Data was then segmented according to the respective task and stimulus onset, oddball task (-1000ms prior to and 2000ms following stimulus onset) or reward based

decision-making (-600ms prior to and 1000ms following stimulus onset). Ocular movement artifacts were corrected by way of independent component analysis (ICA). Following ICA, EEG data was reconstructed by interpolating any previously removed channels, utilizing the spherical splines method. Shorter epochs were then constructed around stimuli presentation (-200ms prior, 600ms following stimulus onset). Segments were centered around the presentation of a frequent or infrequent circle, in the oddball task, and around the win or loss feedback, in the reward based decision-making task. All segments underwent baseline correction according to a 200ms window prior to stimulus onset. Artifact rejection parameters were applied to each segment, marking and removing segments with gradients greater than 10uV/ms and/or 150uV absolute within segment difference.

ERP waveforms were created for each participant and respective task/segment of interest. Respective, segmented EEG data was averaged for each electrode, and utilized for creating difference waveforms. Difference waveforms were created by subtracting the frequent waveforms from the infrequent waveforms in the oddball task, and subtracting the loss waveforms from the win waveforms in the reward-based decision-making task. Grand average waveforms were created by averaging corresponding waveforms across participants.

Components were quantified by identification of maximal deflection from 0uV on the grand average waveform in the timeframe of the component and at the channel where deflection was maximal: N200, 180-240ms at Pz; P300, 360-400ms at Pz; Reward Positivity, 280-320ms at FCz).

CHAPTER THREE: RESULTS

In line with prior validation of both oddball and decision-making tasks, the N200, P300 and reward positivity were found to be reliably elicited following visual inspection (Krigolson et al., 2017). When comparing average peak amplitudes of the N200 and P300 differences waves, both were different from zero, according to respective independent samples t-tests: N200, $t(50) = -4.53$, $p < 0.00$; P300, $t(50) = 16.98$, $p < 0.00$. Average difference waves for reward positivity peak amplitudes were different from zero following an independent samples t-test, $t(50) = 9.84$, $p < 0.00$. Average latencies for each component of interest fell within anticipated temporal windows for each component: N200, 282.27ms; P300, 396.78ms; reward positivity, 305.33ms.

3.1 Oddball Results

3.1.1 N200 Latency

Similar to the other two components, no correlation was found for peak latencies of the N200 component [$F(2, 16) = .33$, $p = .72$]. The N200 expressed differences between the previously concussed groups and the healthy controls, but not in ways I would have anticipated. The healthy controls had a mean of 282.35ms, 95% CI [259.57, 305.14], the group who sustained a single incident of injury a mean of 287.76ms, 95% CI [265.56, 309.97] and the group with a history of multiple concussions a mean of 276.71ms, 95% CI [261.21, 292.20].

3.1.2 N200 Amplitude

N200 peak amplitudes yielded much of the same, no significant differences were found between groups for the three conditions [$F(2, 16) = .82$, $p = .45$]. The mean for the healthy, control group was -2.07uV, 95% CI [-3.31, -0.83] with the mean amplitudes for both concussed groups being more negative. The group with a single incident of concussion had a mean of -4.08uV, 95% CI [-7.70, -0.46] and the group with history of multiple concussions was -4.18uV,

95% CI [-7.17, -1.19]. See topographic maps (Figure 5) showing visual voltage differences between groups.

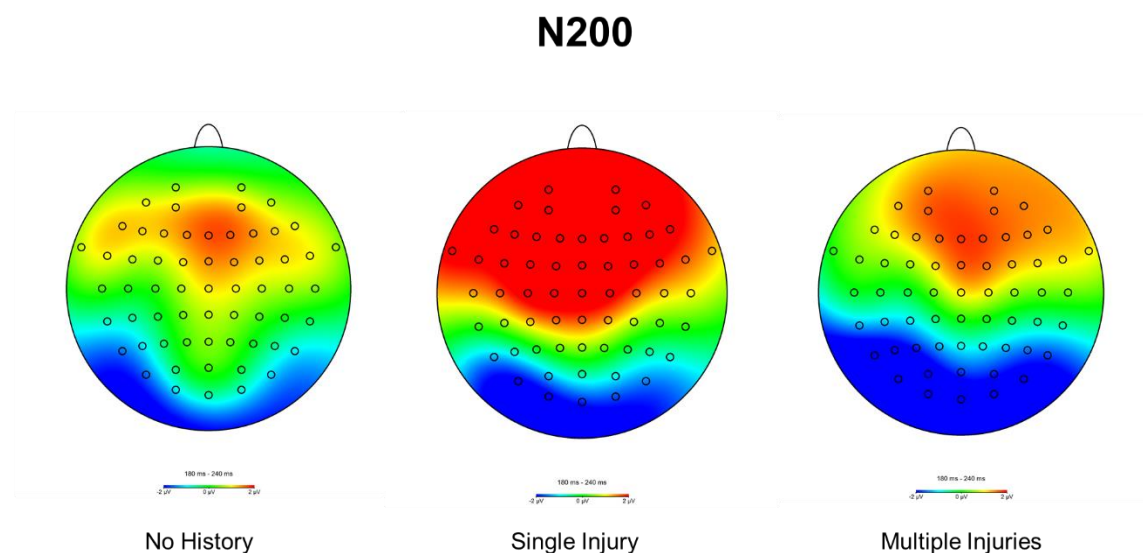


Figure 5. Topographic maps showing voltage differences between groups (180-240 ms post stimulus.)

3.1.3 P300 Latency

Contrary to expectation, no significant differences were found between groups for P300 peak latency values [$F(2, 16) = .45, p = .64$]. According to questionnaires, the control group of healthy individuals with no history of concussion ($n = 17$) had a mean value of 391.06ms, 95% CI [375.27, 406.84]. While not significant, both concussion groups had peak latencies slightly longer than the healthy, control group. The group with a single incident of concussion ($n = 17$) had a mean value of 397.41ms, 95% CI [382.80, 412.03], whereas the group with a history of multiple concussions ($n = 17$) had a mean value of 401.88ms, 95% CI [381.19, 422.58].

3.1.4 P300 Amplitude

No significant correlation was found between groups for P300 peak amplitude [$F(2, 16) = .04, p = .96$]. The control group with no history of concussion ($n = 17$) had a mean of 12.09 μ V, 95% CI [9.18, 15.01]. Peak voltages were decreased in both groups with a history of a

concussion; the group with a single incident of concussion ($n = 17$) had a mean of 11.81 μ V, 95% CI [9.61, 14.02] and the group with a history of multiple concussions ($n = 17$) had a mean of 11.60 μ V, 95% CI [8.95, 14.26]. See Figures 3 and 4 for conditional waveforms and a comparison of both N200 and P300 difference waves for each group, respectively.

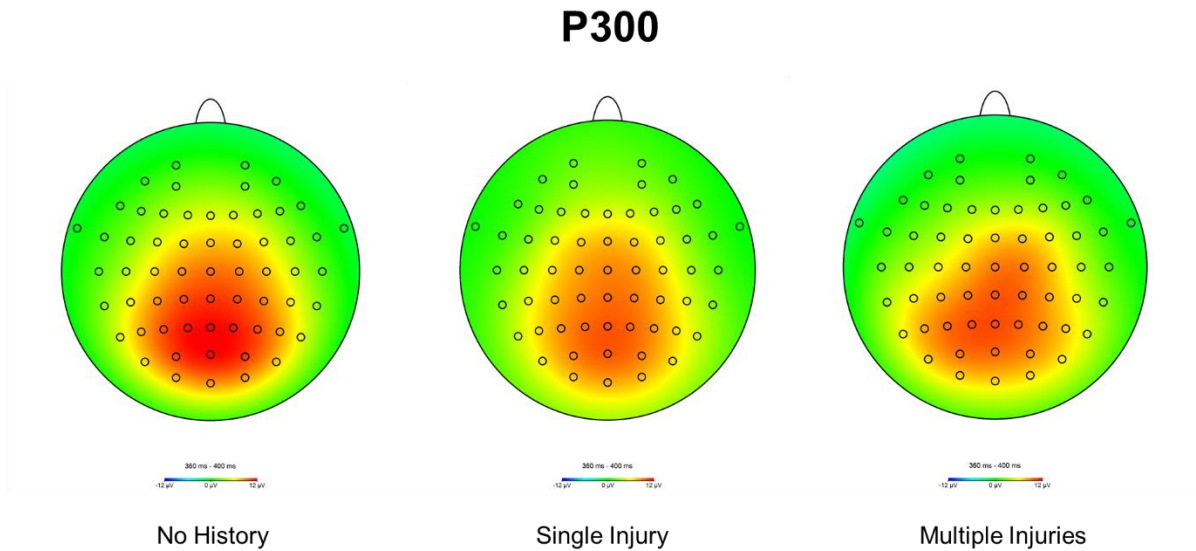


Figure 6. Topographic maps showing greater voltage for the P300 component in the posterior region (360-400ms).

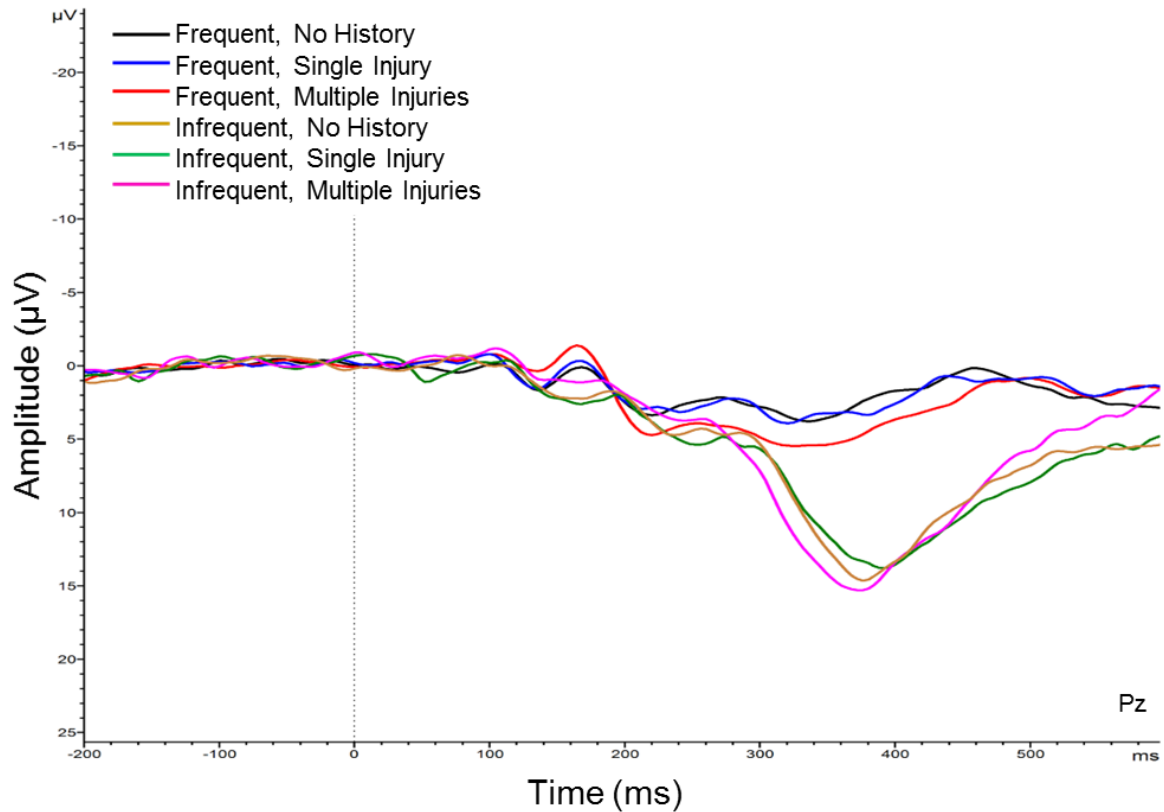


Figure 7. Conditional waveforms for each respective group during the Oddball Task, in which the N200 and P300 were analyzed. In general, a visual comparison shows an anticipated difference in the P300 where infrequent trials yield a more positive deflection than frequent trials.

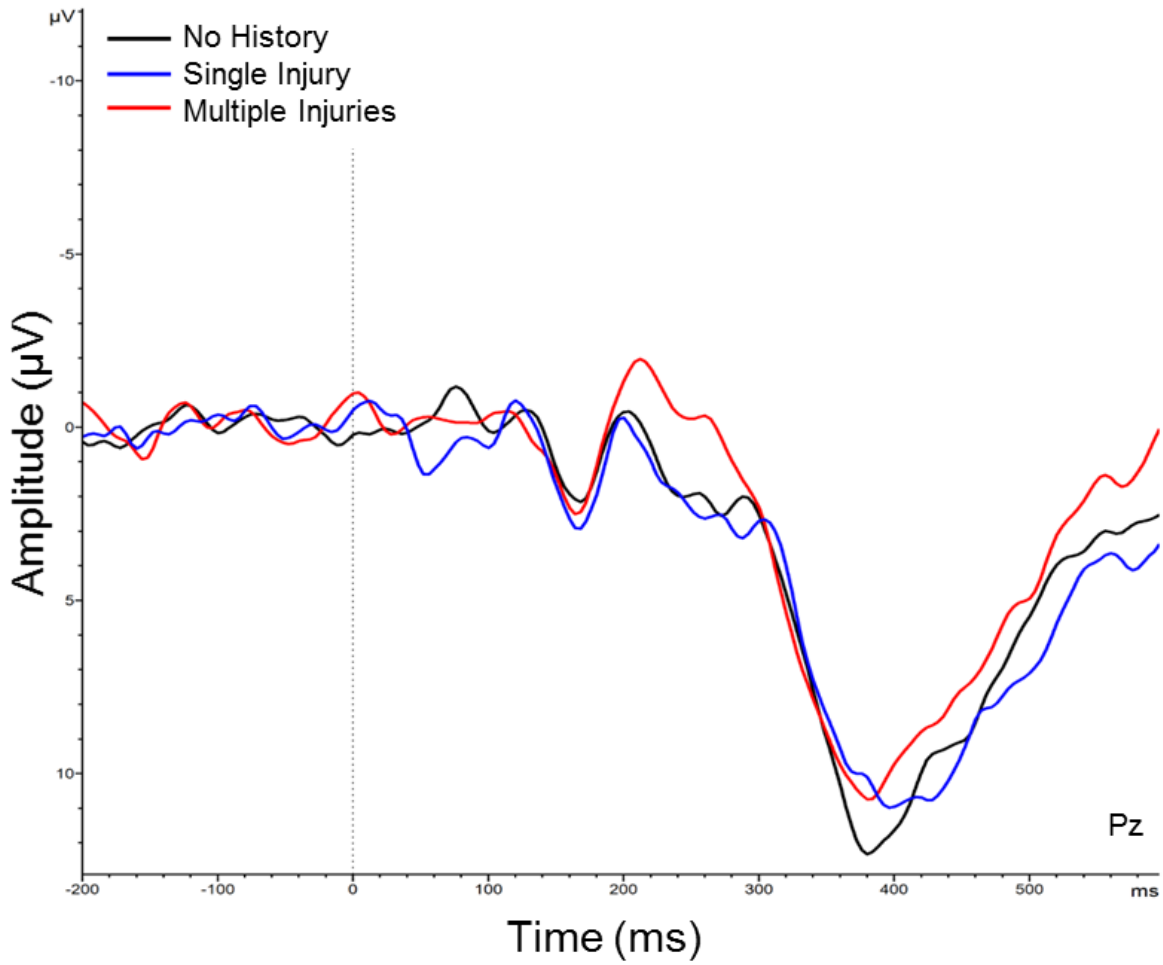


Figure 8. Difference waveforms for each respective group during the Oddball Task, which elicited components of interest, both the N200 and P300.

3.2 Decision Making Results

3.2.1 Reward Positivity Latency

Peak latency for the reward positivity yielded no differences between any of the groups, $[F(2, 16) = .96, p = .39]$. Latency values for healthy controls were, however, less than those for both concussed groups. Mean value for the healthy control group was 299.29ms, 95% CI [282.71, 315.88]. Interestingly, the group with a single incident of concussion yielded a more delayed latency than the group with a history of multiple concussions. The group with a single incident of concussion yielded a mean of 314.59ms, 95% CI [289.66, 339.51], whereas the group with a history of multiple concussions had a mean of 300.47ms, 95% CI [289.37, 311.57].

3.2.2 Reward Positivity Amplitude

Voltages for the reward positivity peak amplitude expressed a trend of decreasing with each group but did not express significant differences, $[F(2, 16) = .21, p = .81]$. The mean for healthy controls was 8.06uV, 95% CI [5.51, 10.61]; mean for group with a single incident of injury was 7.30uV, 95% CI [4.71, 9.88]; and the mean for the group with a history of multiple concussions was 6.82uV, 95% CI [3.37, 10.27]. While a difference was anticipated between both the healthy group and those with a single incident of injury, in comparison to those who sustained multiple injuries, no significance was found ($p = .81$). See amplitude differences for reward positivity difference waves, for each group in Figure 10 and Figure 11.

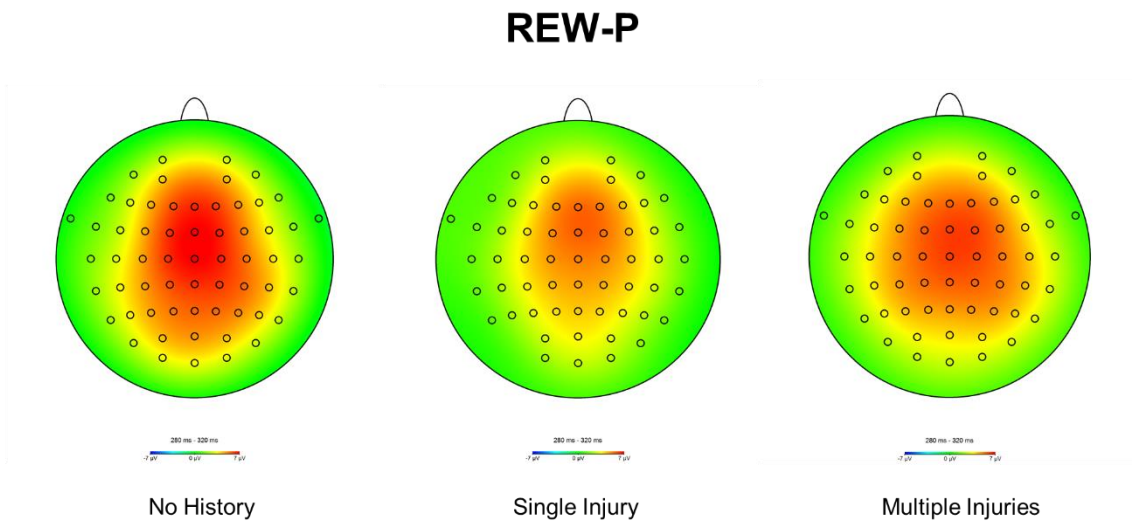


Figure 9. Topographic maps taken between 280-320 ms following feedback presentation, showing voltage differences in the frontocentral area of the brain.

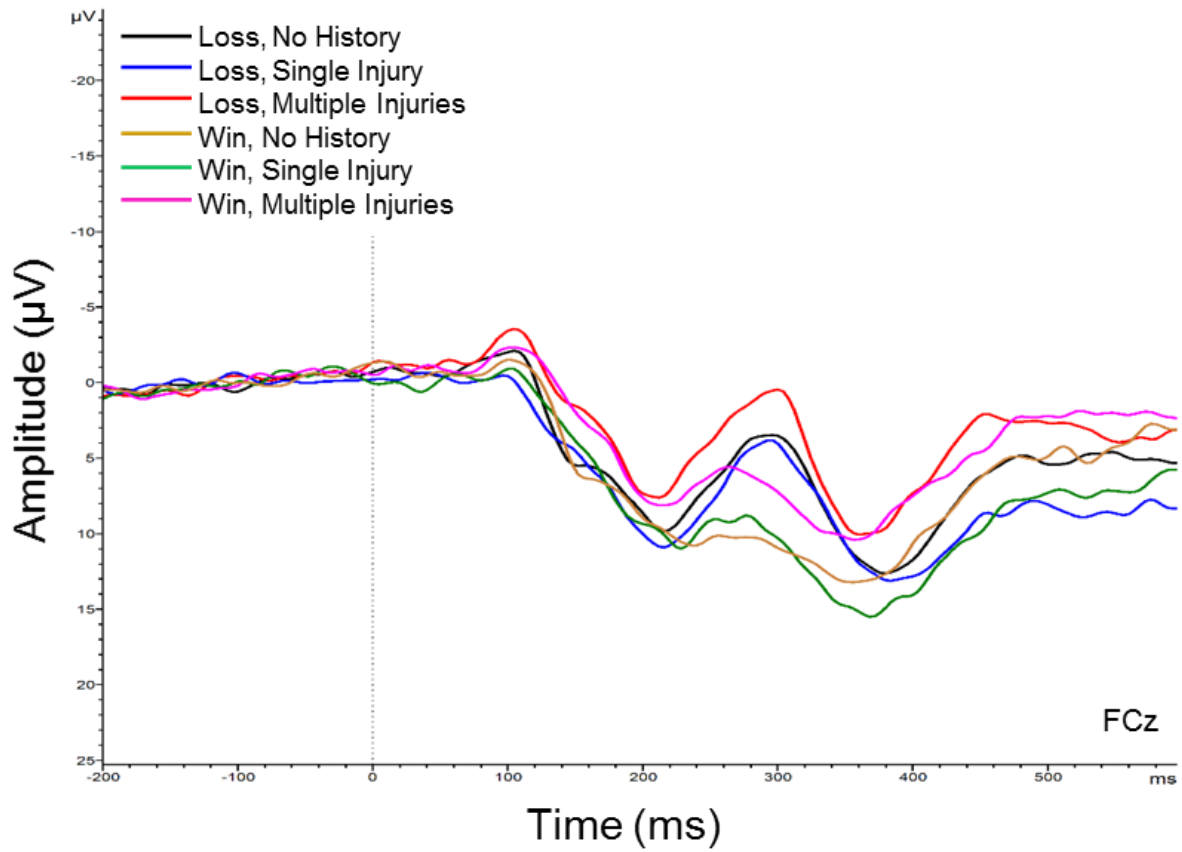


Figure 10. Conditional waveforms for each group for both the 'win' and 'loss' conditions in the decision-making task.

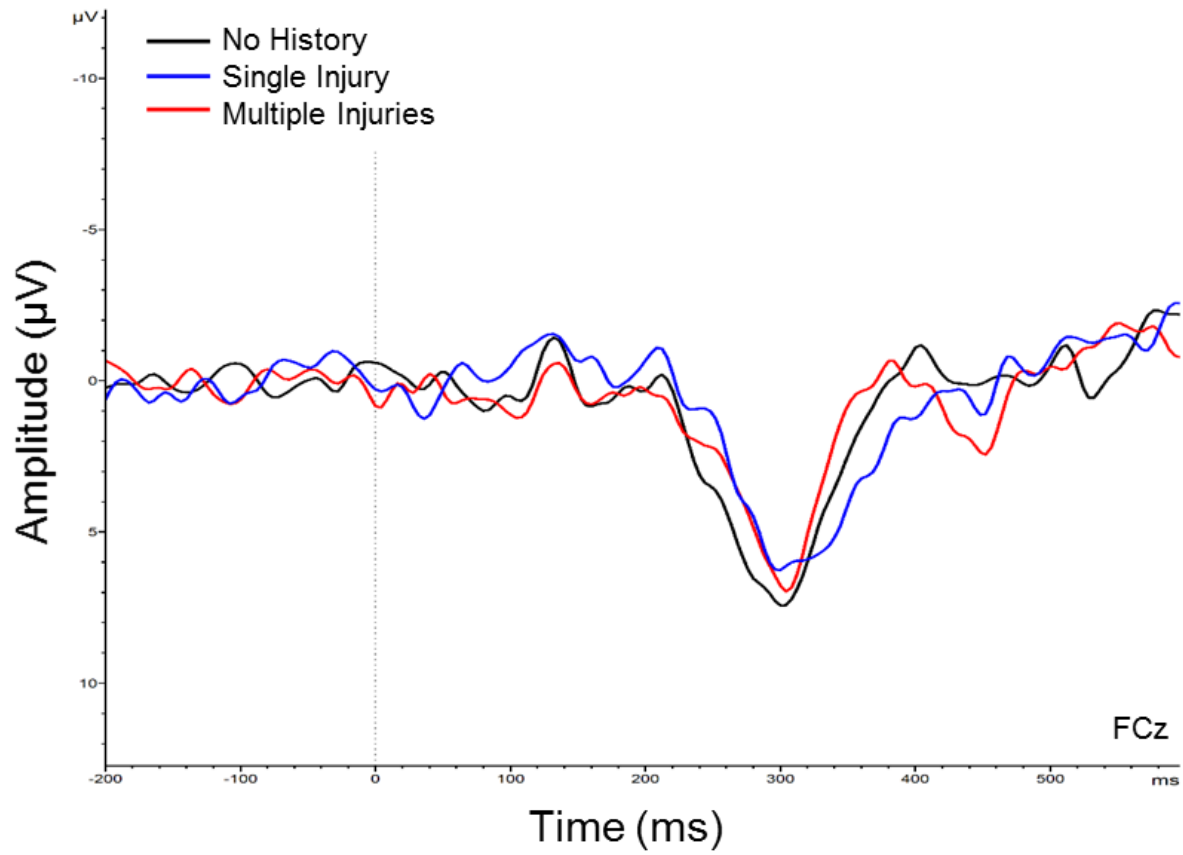


Figure 11. Difference waveforms for each respective group, highlighting the reward positivity component.

CHAPTER FOUR: DISCUSSION

4.1 Summary

Contrary to expectations, no significant differences were found between groups with a history of concussion in comparison to the healthy controls. Moreover, there were no differences between the group with a single incident of concussion and those with a history of multiple concussions. Interestingly, the peak latencies for the N200 and reward positivity were more delayed for the group with a single incident of injury than both the control and group with a history of multiple concussions. Aside from these two nuances, the directionality for the components and peak amplitudes is in line with prior findings, which found attenuated peak amplitudes and delayed peak latencies.

4.2 Significance

While concussions are becoming more frequently discussed in the media due to sport-related injuries, everyone is susceptible. High prevalence rates, which are likely underestimated, have understandably lead to concussions garnering the title of a ‘silent epidemic’ (Langlois et al., 2005). Recent studies continue to highlight the consequential impact multiple head impacts have on individuals, including prolonged recovery times, more severe symptoms and in acute cases, mild cognitive impairment (Covassin et al., 2013; Guskiewicz et al., 2005).

Resultingly, need for a more reliable measure of concussion recognition is critical and time-sensitive. A more consistent identification method would assist patients in numerous ways, improving symptomology comprehension and management, decreasing duration of recovery, assisting with reintegration into society and by limiting financial burdens to the patient and medical institutions.

Previous research has validated ERPs as one of the most sensitive methods for

distinguishing differences in cognitive, sensory and information processing subsequent of a head injury. In comparison with more commonly utilized imaging techniques, such as CT and MRI scans, ERPs offer increased temporal resolution and are able to discriminate between the most common and subtle neurophysiological impairments. The ability to assess functional brain activity make ERPs an exceptional diagnostic measure, allowing technicians and clinicians to perceive changes to informational processing in real time.

4.3 Task Results

In this study ERPs were recorded during two experimental tasks to determine if differences existed between individuals with a history of concussion, in comparison to those who were healthy and never had sustained a head injury. Furthermore, interest was to survey whether differences could be seen between participants with a single incident of injury compared to those with multiple concussive injuries. Previous studies have examined athletes, fewer have examined differences within the general population, a group which sustain concussion via a broader spectrum of biomechanical injuries.

Contrary to findings by Gaetz and colleagues, findings in this study did not show correlation between participants with a history of multiple concussions yielding any noticeable ERP deficits (2003). While there were several confounding variables to address, including a limited sample size, these factors reflect the current nature of ERP and concussion research, which as a whole is inconclusive.

4.3.1 Oddball Task: N200

It was anticipated that the N200 peak amplitudes for participants with a history of concussion would be attenuated, following previous research which has shown concussed participants yield smaller amplitudes in comparison to their healthy counterparts. In the study by

Broglia and colleagues, a novelty oddball task was utilized, including three different stimuli (2009). This may explain why differences were found by Broglia, but not in the present study. Rather than just having targets vary by color in the current study, Broglia used a smaller triangle as the oddball and inverted version as the frequent stimuli. However, a novel stimuli (line figure drawings) was included, increasing need for response inhibition and cognitive demands. Prior research has shown task difficulty has an effect on performance for individuals with a history of head injury (Bernstein, 1999). Results were in line with previous findings, the N200 peak amplitude was visibly smaller

No significant differences were seen between groups for N200 peak latencies, a result which was not anticipated, seeing as previous studies have found a history of concussion yields a greater latency due to difficulty distinguishing attentional processing (Duncan et al., 2005). In a study examining complex visual processing, peak latencies were delayed for complex stimuli paradigms, however, no differences were seen between the healthy control group and those still expressing concussive symptomology (Lachapelle, Bolduc-Teasdale, Ptito & McKerral, 2008). This difference may be due to the presence of symptomology in Lachapelle's study, whereas the current study only examined participants with a history of concussion.

Part of the differences seen between this study and others which found significance may be due to a confounding variable of age on the N200. The N200 peak amplitude has been shown to decrease with age, likely due to physiological development and maturation (van der Stelt, Kok, Smulders, Snel & Grunning, 1998). Not having found any differences between groups suggests that the stimulus distinction and identification may not be as impaired as previously thought in individuals with a history of concussion.

4.3.2 Oddball Task: P300

It was anticipated that individuals with a history of concussion would yield attenuated P300 amplitudes in comparison to 'healthy' controls with no history of head injury. Furthermore, it was expected that individuals who sustained multiple concussions would express an even greater reduction in their P300 amplitudes than those with a single incident of injury, as previously observed (De Beaumont, Brisson, Lassonde & Jolicoeur, 2007; Duncan et al., 2005, Lavoie, Dupuis, Johnston, Leclerc & Lassonde, 2004). Contrary to expectations, results yielded no significant differences in P300 amplitudes across the three groups. Results were directionally in line with previous findings, in which healthy individuals elicited P300 waveforms of greater magnitude than those with a history of concussion. As anticipated, individuals with a history of multiple concussion had smaller amplitudes than those with a single incident of injury, however, the difference was minimal.

Examination of P300 latency, again, yielded no significant differences between groups. Trends, however, expressed a more drawn out latency for participants with a history of concussion, particularly those with a history of multiple concussion. Spikman (1999) referenced extended latencies as responsible for generalized slowness of stimulus discrimination and categorization rather than information processing, as seen by attenuated P300 amplitudes. A review by Gaetz and Bernstein found that P300 latency may be the most sensitive to deficits following brain injury (2001). This may be due to the nature of prior studies utilizing discrimination tasks which are more cognitively demanding.

Minimal differences between the single and multiple concussed groups may be due to a variety of reasons, markedly these may be due to the heterogeneity of concussions and an even greater sample population that was utilized for this study. Participants with a history of multiple

concussions may have sustained a couple less severe injuries that impacted their cognitive function to a lesser extent than an individual who sustained a more serious, single injury. This also could be due to the task not being challenging enough. Duncan et al., found that a more challenging task yielded greater reduction in P300 amplitude (2003).

Nonetheless, a failure to find significance differences between the groups for P300 amplitude suggests contextual updating (of the parietal cortex) may not be as impaired in the long term, for individuals who have sustained a single or multiple concussions. Attentional resources are critical for processing infrequent and rare events. Results from this study suggest that deficits in attentional resource allocation may not be as great as previously thought. Further examination would benefit from surveying participants' depression scores. Prior research found an inverse relationship between P300 amplitude and depression scores (Gosselin et al., 2010).

4.3.3 Decision Making Task: Reward Positivity

The second main component of interest was the reward positivity. As with the P300, no significant differences were examined between groups for reward positivity amplitude. There was an observable trend of decreasing amplitude with the healthy controls exhibiting the greatest reward positivity and the history of multiple concussion group expressing a diminished peak. Differences in elicitation of the reward positivity may be due to a variety of factors. However, prior research has correlated diminished reward positivity amplitudes with children with ADHD (Umemoto, Lukie, Kerns, Muller and Holroyd, 2014), as well as children and college aged students with depressive symptomology (Foti & Hajack, 2009; Bress, Smith, Foti, Klein & Hajack, 2012). The correlation between ADHD, depression and concussion lie within symptomology, including impulsivity, depression, frustration and irritability (Levin & Krasu,

1995). Many of the symptoms of both ADHD and depression, overlap with that of a concussed patient.

Prior imaging studies expressed that regions implicated in the reward phase of tasks, which is associated with the reward positivity included the amygdala and orbital and medial frontal cortexes; these regions have been shown to be negatively affected in individuals who have sustained brain trauma (Proudfit, 2015). While differences were not shown to be of great magnitude, further examination of how the reward positivity is impacted following a brain injury needs to be sought out. The ACC has previously been described as responsible for top-down control of executive functioning. This may justify why deficits are not seen in the reward positivity but in other executive functioning which sit below the hierarchy of the ACCs control. The reward positivity waveform and reward processing are understood to be tightly correlated with a variety of neural networks. Rather than affecting a single region of the brain, an injury to such an extensive network system may allow other streams to act as compensatory mechanisms.

Not having found differences between the reward positivity and the three participant groups supports prior findings of the ACC being part of a much larger network of neural systems, including the midbrain dopamine system and dorsolateral prefrontal cortex (DLPFC). The most common head injuries are those which are diffuse and consequently not focal to a region. Rather than localization, deficits exhibited in the execution of task-related objectives and decision-making tasks may be dispersed throughout these systems, as is the nature of the diffuse injury, itself.

CHAPTER FIVE: LIMITATIONS

As with any study, limitations are anticipated. However, with clinical research and even more so, research on head injury, limitations and confounding variables are numerous. In hindsight, there were issues with some personal choices made regarding surveys and other variables. The challenging nature of head injuries is present across all disciplines, from peers in a social setting to medical professionals seeing patients in an emergency room. Generally, if it cannot be seen, there is great debate as to the root cause and resultant symptomology of the injury. Current imaging methods do not confidently allow for confirmation of all head injuries, causing diagnosis to rely on self-report measures. Including survey methodology, other discussion on limitations will include injury details, age, gender and task.

5.1 Survey Methodology

The single greatest limitation in this study was the survey used. In general, the three most employed methods for assessing a head injury include the GCS, SCAT-3 and the ImPACT. The Concussion Survey was derived from narrowing down feasibility of surveying students efficiently in a laboratory setting. The end goal was to develop a questionnaire that could be given in association with a brief task immediately off the pitch, battlefield or in an emergency department setting that utilized few resources and ten minutes.

Utilizing the GCS would not have applied to the current study due to the nature of administration. Trained staff are required to score patients on consciousness levels according to their responsiveness. Given directly at the time of injury, the GCS assumes some lapse of cognitive function and therefore, even the highest score of 15 classifies a 'mild' injury. A 'mild' head injury requires the patient have spontaneous eye opening, can maintain normal conversation and have typical motor responses. Participants that came in for this study were not walking in

directly following an injury, rather they either were healthy or had a history of injury. All were spontaneously in control of opening their eyes, maintained normal conversation and had characteristic motor responses. Utilizing the GCS with participants that were healthy and/or those with a history of concussion would have marked them as having a 'mild' head injury, not benefiting attempts to make correlations between groups.

The ImPACT examination is frequented for post-concussion assessment, however is limited in both financial and time constraints. Athletes are typically the main population utilizing the ImPACT examination and take it prior to the onset of their season and following an injury. Normative ranges may be used to compare an individual's results to a general population if they do not have a baseline. However, the establishment of ImPACT was to provide comparative, within subject ratings for individuals, in the event of an injury being sustained. Currently, this is an immense setback within concussion research. Too often most of the studies which have been conducted have been between-subject designs and are comparing age-matched participants due to limited populations and time. As with a majority of clinical studies, concussed populations are unanticipated in comparison to intervention studies. Current examination of deceased football players expressing CTE appears highly correlated when comparing them to the general population. However, it's critical to take heed not to justify causation based on correlation, especially when the sample population is being carefully picked by families who have noticed cognitive changes in their loved ones. In concussion research the most effective method is to compare the participant to themselves due to heterogeneity of clinical cases. Further investigation of head injury would benefit greatly from longitudinal, within subject studies following participants over decades.

The SCAT-3 is currently the standard protocol for concussion diagnosis in sport.

Comprised of a symptomology scale, as well as working memory tasks and motor reaction time, the SCAT-3 does not assess previous concussion history nor details, due to being used to assess a current injury, immediately following an incident, if not days following. As is, with intentions of utilizing a brief questionnaire, only the symptomology portion was utilized. Consensus has shown that the symptomology list is beneficial for tracking recovery (McCrory et al., 2017).

As with other clinical populations, studying concussion bears consideration of multiple confounding variables due to the heterogeneity of the injury itself. These variables include time since injury, mechanical forces, severity and locus of injury, genetics, gender and previous injuries, to name a few. This study aimed to account for as many of these factors possible through the ‘Concussion Survey,’ however, not all variables were able to be controlled, nor were all taken into the same level of consideration. The concussion survey sought to screen participants for any cognitive or psychiatric disorders, current medications which may have impacted ERP results and briefed participants on their concussion history, if they had any. In retrospect, these questions were limiting due to their open-ended nature.

5.2 Injury Details

Time since injury was requested from participants, however, not controlled for, nor included in final analysis. As referred to, the question of interest resulted in too many open-ended responses, limiting reliability of what we could and could not be controlled for. Responses included the exact month of injury while others ball-parked a handful of years and specific dates of injury were not obtained. While this information would have been of interest, I am confident it was not critical in final analysis. Previously, visual oddball tasks showed no correlation in respect to time since injury (Duncan et al., 2003). Furthermore, if the participant pool only included individuals with a single incident of concussion, time since injury would have been

more easily controlled. However, controlling for time since injury and time between injuries in participants with multiple concussive incidents would have required a much greater participant pool to achieve feasible, statistical power.

For these reasons, it must be considered that the multiple history of concussion group classified participants as the ‘same,’ even if they had sustained multiple injuries within a two-week or a two-year span. This is extremely important to acknowledge; general consensus is concussive incidents are cumulative in nature. Multiple injuries occurring within a short timeframe of one another when complete healing has yet to occur, have shown extremely detrimental effects on performance and memory in athletic populations (Iverson 2004). For participants with a history of multiple concussions, particularly in this study, there is no method to quantify the magnitude of their prior injuries, severity, symptomology and how those impacted subsequent injuries.

5.3 Gender

The majority (70%) of participants in this study were females. While studies are limited examining the influence of gender on concussion, prior research has suggested that females experience concussions and increased symptomology following an injury (Dick, 2009). A study examining the relationship between gender and recovery a year following concussions found that women performed better than their male counterparts in working memory, language and attention. Results suggest that women may recover from concussive incidents more efficiently than men (Ratcliff et al., 2007). In this study, with such a high portion of participants being female, it is not unlikely that not finding any correlations may be due to a difference in gender and recovery. Other possibilities include females who participated in this study were too far removed from the time since their injury, or they may not have experienced as severe head

injuries.

One of the several potential issues between genders is the difference of the physics behind head injuries which each gender typically experiences. Females have been shown to sustain a greater amount of absolute concussions, however, males received a higher number of concussions resulting from player to player contact (Dick, 2009). The biomechanical impact is going to yield different effects, i.e., blunt force injury vs. acceleration/deceleration of a whiplash type injury. Injuries sustained from contact with another player must take into account the additive physical forces of not one but two moving bodies, versus collision with a stationary object.

Although limited, prior research suggesting women sustain a greater number of injuries may not be all too reliable. While there are ideas as to why gender differences may exist, including biomechanical forces, hormonal differences and openness/responsiveness post injury, there is no conception of the differences within the physiological underpinnings as to why these differences may exist. Currently, the only recognized anatomical differences between genders which may impact a concussion is muscle tissue in the neck and resultant neck strength. Tierney and colleagues examined the effect of head protection in performing soccer heading exercises. Women not only had less neck strength in comparison to their male counterparts, but had increased head acceleration up to 40% greater than males (2008).

5.4 Age

Additionally, a difference in age between groups may justify why the N200 and reward positivity peak latencies were highest for the group with a single incident of concussion, rather than the multiple concussed group. Giedd and colleagues have found that cortical gray matter of the occipital lobe can continue to develop into an individual's early twenties (1999).

5.5 Tasks

The task participants went through was much more abbreviated than usual ERP tasks and in conducting future studies it would be suggested to use a more cognitively demanding task (Duncan et al., 2003; Gaetz 2000; Gosselin et al., 2010). The brief nature of the tasks was to pilot an immediate, off-the-field and/or at the scene of an accident screening tool. Currently, medical, quantitative methods for screening head injuries are limited to hospital settings (some ambulatory monitoring). Otherwise, go to protocol includes self-report, neurocognitive and motor assessments. As previously mentioned, each of these have less than ideal reliability, especially for an injury which has reached epidemic levels. In 1983, Coi and colleagues reviewed prediction model databases for severe head injury. All of which had been developed retrospectively, and did not reveal reliability in identifying prospective outcomes of concussion (1983). While medical technologies have advanced greatly over the last couple of decades, there is yet to be a single, consistently reliable method for concussion detection.

If there was a single confounding variable elucidating challenges with concussion research and diagnosis it would lie in the definition of what a concussion is. Historically, one of the most common requirements for a head injury was that a loss of consciousness was required. However, with time and an increase in knowledge, we now understand that even severe symptomology can occur without the patient having experienced a loss of consciousness.

There is no universally accepted definition for a concussion due to the nature of injury being so heterogenous. Due to this, comparison of incident rates and factors are extremely averse. To make matters more challenging, head injuries have different definitions according to respective domain, such as in a military, sport or emergency department context. Within these,

there can also be discrepancies of what constitutes a concussive injury. This is due to the various nature of injuries and including population differences.

5.5 General Points of Interest

The reliance of concussion recognition and management on self-reporting measures is an extremely consequential one. Out of all medical diagnoses, head injuries are one of the few where the medical professional must rely on the injured patient to make their diagnosis. A broken leg is visible on an x-ray, a hemorrhage is visible on a CT scan and a bacterial infection can be diagnosed through cell cultures. The most common and mild concussions, however, more than likely will not be identified on a scan due to their diffuse nature. However, the injured patient will be diagnosed according to how well their injured brain can describe previous and current deficits.

General limitations apply to this study, as well, however, sample size was not a concern. An a-priori power analysis indicated a sample size of 15 participants in each respective group would be adequate to distinguish a significant difference with power of .97 and alpha of .05 (Faul, Erdfelder, Buchner & Lang, 2009). In the future, efforts would be made to concentrate on a more particular population, such as a sports team or more ideally, seek out a population from the hospital with consistent and known head injury diagnoses. As is, a varied population makes the confounding nature of what type of injuries were sustained of greater concern for the reliability of their results in comparison to one another, some participants were in skiing accidents, while others lightly bumped their head on a table when they were a child. The obstacle of focusing on a particular population is a limitation of time. As previously mentioned, concussions are not an injury which can be anticipated or studied in an intervention based case. Rather, requires investigators to wait for an injury. If a study is being conducted on a single

team, over the course of one year there may two athletes who sustain a concussion. Additionally, studies of utmost need are within subjects, meaning that not only can athletes be compared to one another, but now additional time is necessary to collect and maintain baseline reports for each participant. Such studies require a commitment of laboratory time and financial support, otherwise, limiting the scope of research to be conducted. Moving forward, changes to the survey, extending the study to a longitudinal, within-subjects design and utilizing a more challenging task battery to increase cognitive demand would be necessary.

CHAPTER SIX: CONCLUSIONS

While no significant differences were found between the healthy group, single incident of injury or multiple concussed group, all hope is not lost. Previous literature is littered with examining ERPs following injury, what remains is confirmation of a consistent task and method for utilizing this technology in the most appropriate way. A study of medical professionals in Ontario supported the notion that current concussion recognition is failing the individuals who are unfortunate enough to fall victim to such injuries (Zemek et al., 2014).

Currently, missed cases, misdiagnoses and misattribution are responsible for numbers which suggest TBI prevalence and incidence rates are of greater epidemic proportions than previously expected. The intention of this study was to progressively work to identify more sensitive and promising methods for evaluation of concussion in athletes whom have yet to demonstrate clinical pathologies. Additionally, the goal was to develop a brief cognitive battery task to provide consistent and reliable detection of head injury. Intention was to utilize a portable system directly off the pitch, combat field or in a home setting.

While ERPs were not found to be a significant measure for differentiating previously concussed participants from healthy controls, multiple factors may have had a role influencing these results. Moving forward, priority would be to amend the current Concussion Survey, to obtain more particular injury information, as well as modifying the task to be more demanding.

Finding a reliable method for concussion recognition is critical moving forward, head impacts without a loss of consciousness have been overlooked for decades. With continued CTE cases breaking into the media, parents becoming increasingly concerned about their children's participation in high risk sports and IEDs constantly evolving to cause the most destruction possible, the risk of sustaining a head injury remains.

Current methods of diagnosing concussion will continue to develop but self-reported

concussion symptomology and history is a key limitation to existing methodology. Appropriate management will only be possible with a multidisciplinary approach.

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APPENDIX A

Concussion/Head Injury Survey

Have you ever been diagnosed with headaches or migraines? Y N

Do you have a learning disability, dyslexia, ADD/ADHD? Y N

Have you ever been diagnosed with depression, anxiety or other psychiatric disorder? Y N

Are you on any medications? If yes, please list: Y N

Have you ever sustained a concussion? Y N

Have you ever been diagnosed with a concussion? Y N

If so, how many concussions have you had? _____

When was/were the concussion(s) received? _____

How do you feel?

“You should score yourself on the following symptoms, based on how you feel now.”

Headache	0	1	2	3	4	5	6
“Pressure in head”	0	1	2	3	4	5	6
Neck pain	0	1	2	3	4	5	6
Nausea or vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
Feeling like “in a fog”	0	1	2	3	4	5	6
“Don’t feel right”	0	1	2	3	4	5	6
Difficulty concentrating	0	1	2	3	4	5	6
Difficulty remembering	0	1	2	3	4	5	6
Fatigue or low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
Trouble falling asleep	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervous or Anxious	0	1	2	3	4	5	6

Total number of symptoms (Maximum possible 22) _____

Symptom severity score (Maximum possible 132) _____

Are you currently experiencing any of these symptoms? Y N