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Cognitive Decline and Contact Sports: The Relationship Between P3 Amplitude and Sub-concussive Head Impact

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Abstract

The present study sought to explore the effect of repetitive sub-concussive head impacts on the P3 event-related potential (ERP) amplitude and measures of movement kinematics. University students participating in collision, contact, and non-contact sports at the club and varsity level completed a cued visuomotor adaptation task. Results indicated that participants who estimated experiencing four or more sub-concussive head impacts per week display a significantly reduced P3 amplitude across both normal and adaptive trials. Additionally, participants who estimated experiencing less than four sub-concussive head impacts per week displayed no significant changes in P300 amplitude between “switch” and “stay” trials. This research helps expand our understanding of the potential cognitive and motor dysfunction which may be associated with prolonged exposure to sub-concussive head impacts and discusses the implications of exposing this population to continued head trauma without adequate understanding of the potential consequences of that exposure.

Keywords: *Cognition, Cognitive-Motor Dysfunction, Concussion, Sub-concussion, American Style Football, Student-Athlete*

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The degree to which Student Athletes, particularly American Football players at NCAA Division 1 programs, benefit the institutions they attend is increasingly well documented (NCAA v. Alston, 2021). This documentation led to the advent of NIL (name, image, and likeness) deals and the Supreme Court Case: National Collegiate Athletic Association v. Alston in 2021. American Universities rely on Student-Athletes for revenue and “largely bar student-athletes from sharing in any of the profits generated by their participation” (Garthwaite et al., 2020, p. 1). Division 1 Institutions typically field a variety of athletic teams numbering around 20. However, approximately 85% of all revenue generated by athletics stems from American Football and Men’s Basketball (commonly referred to as revenue-generating sports) (Garthwaite et al., 2020). In return for the value that Student Athletes provide for their institution, those same institutions must prioritize the understanding and investigation of the consequences that student-athletes face on account of their participation in contact and collision sports.

A concussion is defined by the Mayo Clinic as “movement of the brain within the skull resulting in brain disturbances.” The long-term effects of mTBI (mild traumatic brain injury), particularly in AmF (American Men’s Football), were first brought to light by Dr. Bennet Omalu in 2005 when he discovered the amyloid plaques, sparse neurofibrillary tangles, and tau-positive neuritic threads that are now used for post-mortem diagnosis of Chronic Traumatic Encephalopathy (Omalu et al., 2006; Omalu et al., 2018). Dr. Omalu’s work increased awareness of the long-term effects of mTBI; however, concussions remain incredibly prevalent and destructive in contact sports to this day. This effect may be partially attributed to the fact that there is no definitive biomarker that can be used for the diagnosis of concussion (Tator, 2013).

Current literature shows well-documented patterns of underreporting of concussions within collegiate sports which may be attributed to a number of factors. In an anonymous survey of collegiate athletes, 43% reported hiding symptoms of concussion from their athletic trainers and coaches, and 22% reported that they would be unlikely to report concussion symptoms (Torres et al., 2013). A separate survey at an alternate group of institutions found that "49.7% of all respondents reported at least one acknowledged, unreported, or potential concussion" (Llewellyn et al., 2014, p. 76). This research allows us to estimate that almost half of all contact and collision sport collegiate athletes will hide at least one concussion or suspected concussion during their collegiate career.

A sports concussion at the collegiate level is diagnosed through clinical examination, reinforced through cognitive and motor performance recorded as clinical assessment tools, and augmented by reassessment using the baseline testing software specific to the institution (Broglio et al., 2018; Liu et al., 2022). The cognitive assessment software used to derive a baseline measure of cognitive function for athletes at the College of William & Mary is the imPACT Test. The imPACT test of the Immediate Post Concussion Assessment and Cognitive Testing is "a computerized test that measures memory, attention span, visual, and verbal problem solving" (IMPACT Applications, Inc., 2022). The purpose of a baseline test is to allow clinicians to compare post-concussion cognitive function to previously recorded data from the individual with the suspected injury to allow every athlete to serve as their own healthy control (Broglio et al., 2018).

In a longitudinal study to investigate the reliability of clinical assessment software for the diagnosis of concussion, including imPACT, Broglio et al. (2013) assessed the overall reliability of current diagnostic tools (including imPACT) as less than optimal. The creators of imPACT clarify that imPACT is not nor does it claim to be a tool capable of decisively diagnosing mild traumatic brain injury (ImPact Applications inc., 2022). The imPACT is marketed as a tool that can be used by qualified medical professionals as one tool out of many factors to be considered for the diagnosis of a concussion. The weakness of current concussion diagnostic tools is that they do not assess cognitive- motor-integration. This weakness is conspicuous because “to be successful in many sports, a player must apply a wide range of cognitive factors to each of their movements within a game” (Hurtubise et al., 2016).

A sub-concussion is defined as “an impact to the head that does not result in immediately diagnosable concussion but can result in later neurological consequences” (Wilson et al., 2023, p.1). As there is no biomarker for mTBI and sub-concussions may be even more difficult to detect, research in sub-concussion requires great innovation and creativity in order to develop methods that may be sensitive enough to detect the cognitive changes that occur.

Recent studies attempting to develop a rodent model of sub-concussion and resulting motor dysfunction or biomarkers have had promising results. Lavender and colleagues (2020) did significant work toward establishing a rodent model for sub-concussion. One crucial aspect of their study was to build upon previous rodent studies of sub-concussion by exposing their subjects to repeated, standardized sub-concussions over a period of time rather than providing exposure to a single sub-concussive impact. Lavender (2020) found that “when the repeated sub-concussion was administered for 12 weeks, the rats demonstrated significant neuromotor dysfunction when compared with the Sham group of rats” (Lavender et al., 2020, p. 4). It is also significant to the current experiment to note that this neuromotor dysfunction was only detectable when using the most challenging and sensitive of the measures used in this experiment.

Taking a more traditional biological approach, Hiles-Murison et al. (2021) exposed rodent subjects to repetitive sub-concussions for a period of two weeks before performing an autopsy to search for post-mortem biomarkers traditionally associated with chronic traumatic encephalopathy. The researchers discovered "significantly increased lateral ventricle volume in the rats with repeated sub-concussion, indicating substantial structural changes occurring in the brain without any symptomatic or neurobehavioural changes" (Hiles-Murison et al., 2021, p. 1). This finding contributed to the growing body of literature detailing that brain damage associated with prolonged participation in contact sports may begin earlier than it can be easily detected.

The motivation for the continued study of the neurological consequences of sub-concussive impacts is the relatively recent discovery of chronic traumatic encephalopathy (CTE; Goldstein et al., 2018). Chronic traumatic encephalopathy, or CTE, "usually presents clinically after a prolonged latent period as a composite syndrome of mood disorders, neuropsychiatric disturbance, and cognitive impairment" (Uschendu et al., 2016, p. 1366). Eighteen years after the groundbreaking discovery of CTE in 2005, we now understand that CTE leads to cognitive dysfunction, declining memory, depression, suicidal behavior, and the development of dementia (Stern et al., 2011). This condition is incredibly severe and warrants further investigation into the long-term effects of sub-concussion. A recent study at the University of Boston investigating CTE found that "20 percent of athletes with CTE had no diagnosed concussions" (Goldstein et al., 2018, p. 1). Even if this finding may be partly due to underreporting of concussions, it highlights the importance of developing an improved understanding of the neural and behavioral consequences of repetitive sub-concussions.

One potentially useful method for detecting neurocognitive changes in college athletes is electroencephalography (EEG). EEG is a highly sensitive physiological measure that has a high level of performance validity (Broglio et al., 2011; Ip et al., 2018). A high level of performance validity refers to the fact that EEG is a measure whose results are highly likely to reflect the true cognitive function of the subject completing the task (Greher & Wodushek, 2017). EEG is a noninvasive method used to measure the electrical fields which are generated by the brain and then can be recorded as they reach the scalp (Richards, 2017). Electroencephalography is a continuous measure and when it is used within the field of cognitive psychophysiology, the recordings taken from the scalp are segmented into responses to specific events. The averaging of those event-related segments is used to measure the event-related potentials (ERPs), which are thought to reflect various sensory, perceptual, and cognitive processes. The P3 component is a positive deflection in the ERP that occurs approximately 300 to 700 MS after the presentation of a stimulus. The topographical distribution of P3 is typically over parietal recording sites and it is frequently split into P3a and P3b subcomponents (Luck, 2013, Ch. 3). P3a is commonly associated with novelty detection and attentional resource allocation, while the P3b is often associated with attention and potentially memory processing (Polich, 2007). P3 amplitude and latency have been shown to be altered in a number of studies associated with sub-concussive and concussive head impacts. (Clayton et al, 2020; Dillon 2017; Brooks, 2016; Dupuis et al, 2000; Lavoie et al, 2004; Hudac et al, 2018; Moore et al, 2017; Gosselin et al, 2012).

Hudac et al. (2018) used a cohort of 36 AmF athletes aged 18-23 responding to a 2-back working memory assessment which is a test of working memory that prompts a response via button press to the presentation of different consonants on a computer screen. Researchers collected electrophysiological recordings during the duration of the task as well, and one-way ANOVAS were then computed in order to compare response time and accuracy between the concussion history and nonconcussion history respondent groups (Hudac et al., 2018). Hudac et al. (2018) found the larger p3 amplitudes within “match” trials as compared to “non-match” trials during a 2-back memory task. Accuracy results from this study indicate that the “match” trials were more difficult for participants overall than the “non-match” trials and the p3 components elicited for data analysis only included correct answer trials. The findings of this study were that athletes with a history of concussion exhibited larger P1 and P3 amplitudes which could corroborate the hypothesis that cognitive dysfunction associated with a history of concussion creates increased demands on cognitive resources which may be seen through selective attention (Ledwidge & Molfese, 2016). The data collected from this investigation led Hudac et al. (2018) to conclude that ERPs may be a sensitive and objective measure to detect the long-term cognitive consequences of concussion.

Moore et al. (2017) used a different population, that of soccer players, to investigate the effects of concussive and sub-concussive impacts on neurophysiological function. Soccer as a population has been chosen historically for sub-concussive research because of the frequency with which soccer players make contact between their heads and soccer balls during practice and gameplay. Moore et al. used a population of 56 male collegiate soccer players and aimed to observe physiological changes correlated to both concussive and sub-concussive impacts. This investigation was motivated by literature detailing that neuropsychological testing produces inconclusive results for the effect of sub-concussions and this led the researchers to pursue the method of electrophysiology. Subjects’ performance was assessed using a visual oddball task with a button press response. Moore et al. (2017) used a three- factor oddball task to elicit the p3 component and found a significant main effect of group for both the concussion group as well as the sub-concussion group in which the concussion and sub-concussion group both showed decreased p3 amplitudes as compared to the healthy control group. The findings indicated that accumulative sub-concussive impacts lead to alterations in neural structure and function, which are detectable using EEG (Moore et al., 2017).

Examining the metrics of reaction time and accuracy, Gosselin et al. (2012) used a task to measure visual working memory to study visuomotor performance of a cohort of 80 participants in which 50% had a history of concussion and 50% did not. Comparison of results showed a significant group difference for behavioral performance in which participants without a history of concussion had significantly higher behavioral performance scores than participants with a history of concussion (Gosselin et al., 2012). In addition to the behavioral measures, they found consistently smaller amplitudes for parietal p3 in the concussion group compared to the healthy control group.

In order to explore more longitudinal effects, Clayton et al. (2020) conducted a four-year study of contact sport collegiate athletes and semi-professional athletes in contact sports to track changes in neurophysiological function over time using electrophysiology. This experiment used an auditory oddball task in which participants used a button press to identify whether the tone they heard was the normal or oddball stimulus. This study found that 88% of concussed players had a significant reduction in P3 amplitude following a concussion. It is also significant to note that suppressed P3 persisted even after reaction time and traditional measures of concussion symptoms recovered.

Similar to the present study, Brooks (2016) used electrophysiology to examine the relationship between sub-concussion and the P3 component. Notably, this study differed from the present study because it surveyed Canadian-style football players, similar to American football; however, it is safer due to several rule differences. The most critical rule difference in Canadian football is that it features three Offensive linemen “down” (with their hands on the ground before the start of the play). In contrast, American-style Football allows four offensive linemen to be in this position. This ameliorates the number of concussions experienced in Canadian football because it decreases the power of the offensive line and also decreases the number of players putting their heads in such a vulnerable position. Brooks studied a population of 45 Canadian football players using a visual oddball task with a button press response. The study grouped participants based on whether they played “skill” or “unskilled” positions and whether they were “small” or “large”. Small skill positions within this study were wide receiver and defensive back; large skill positions were linebackers, running backs, fullbacks, and quarterbacks. The large unskilled group was composed of offensive and defensive linemen. This study conducted assessments during pre-season, mid-season, and postseason. The researchers found that small skilled and large skilled players showed a significant decrease in P3b amplitude at their mid and post-season evaluations despite all positions receiving some level of collision throughout the season. The researcher hypothesized that impacts received by the small and large skill groups might be in more harmful locations or could be of a higher velocity in order to explain the amplitude differences.

Increased difficulty performing context-updating processes in trials that necessitate task switching is associated with decreased cognitive flexibility. In turn, decreased cognitive flexibility is a known post-concussive symptom (Lucas, Killgore, Daily, 2020). Task switching capability is a component of executive function which is significant because “executive dysfunction is among the most common and disabling aspects of cognitive impairment following traumatic brain injury” (McDonald, Flashman, Saykin, 2002, p. 1). The P3 component of electrophysiology is believed to change somehow as a function of task switching; however, conflicting theories exist as to what exactly that change looks like. Gajewski and Falkenstein

(2011) highlighted two conflicting beliefs about interpreting p3 as a measure of task switching. One explanation is that the P3 amplitude will decrease when the processing of a target requires greater effort, such as a "switch" trial in which the subject must adapt to a cue that is different from the one they saw in the previous trial (Kieffaber & Hetrick, 2005). Within the current study, "switch" conditions will be defined as trials in which the task is different than those of the trial that came before it. Within the current study, "stay" conditions will be defined as trials in which the task presented to the participant is the same as the task that came before it. These two conditions will be compared in order to evaluate switch-costs in accordance with the findings of task-switching literature (Gladwin et el., 2006; Kieffaber & Hetrick, 2005). We hypothesize that the "switch" condition will elicit a higher p3 amplitude (as compared to "stay" condition) for all participants, regardless of concussion or level of sub-concussion.

In addition to neurometric measures like the P3 component, behavioral measures of movement fluidity may also be important indicators of cognitive change with sub-concussive injuries. Complementing research investigating sub-concussion related motor deficits in rodents, the current study will use measures of movement fluidity in order to quantify participants' motor performance. Fluidity was chosen as the measure to be examined because smoothness is considered to be a hallmark of healthy movement (Salmond et al., 2017). It is important that this study uses both coupled and decoupled movements because Previously concussed elite-level athletes may have persistent neurological deficits that cannot be detected using standard clinical assessments alone (Hurtubise et al., 2016). Traditional methods of concussion assessment use basic measures of cognitive and motor function which are not sensitive enough to detect deficits in a population with significantly elevated motor capabilities such as athletes. Sergio et al. (2017) suggested that this shortcoming of traditional assessment methods can be at least partially attributed to their failure to assess the concurrent processing of motor and cognitive function (cognitive-motor integration, CMI).

This led Hurtubise et al. (2016) to explore cognitive-motor-integration abilities using "decoupled movements". An example of a decoupled movement is the way that one moves a cursor horizontally across the horizontal plane of a desk in order for the cursor icon itself to then move horizontally across the vertical plane of a computer screen. This is an example of a movement that has been decoupled on one level. However, it is also possible to decouple movements to a higher degree. Hurtubise et al. (2016) utilized decoupled movements because "the ability to produce decoupled movements is shown to be more vulnerable than the ability to perform standard visuomotor mapping in some forms of clinically altered brain function" (Hurtubise et al., 2016, p. 2). The researchers believed it was important to create a more difficult cognitive-motor-integration assessment when collecting data from a population of elite athletes on account of the previous findings, which detailed the lack of adequate sensitivity in traditional concussion assessments. In their trials testing decoupled movement, scores of movement fluidity were significantly decreased for participants with a history of concussion.

Taken together, the research on neurometric markers like the P3 ERP component and sensitive behavioral measures like fluidity in decoupled movement show promise for the development of better measures of sub-concussive injury. Thus, the current study focuses on the measurement of specific ERP amplitudes in conjunction with cognitive motor behavioral measures. The current study employs a cued visual search task in order to elicit the P3 component. The visual search task used in this experiment requires the participant to move a computer cursor in order to select the cued target stimulus from among distractors. In some trials, the cue indicated that the cursor's movement would be decoupled from the participant's hand movement. We wanted to ascertain whether the participants with a higher number of concussions or subconcussion would display jerkier movements than participants with little to no experience with concussions or sub-concussions. We predicted that participants with a higher number of sub-concussive impacts would display jerkier movements as compared to participants with a lowe number of sub-concussive impacts. We also predicted that an increased volume of sub-concussive head impacts would be correlated with a decreased p3 amplitude.

Method

Participants

A total of 15 participants were recruited from the campus of the College of William & Mary. Participants were recruited from the SONA participant pool as well as using a promotional flier for the study. All participants were over 18 years of age and understood and consented for their data to be used in this project. All participants were participants in either varsity sports or club sports. The sample included 9 participants who self-identified as male and 6 who identified as female. All participants were screened for current symptoms of concussion using standard clinical symptom checklist for the domains of cognition, sleep, emotion, and physical symptoms. Exclusion criteria included the self-reporting of current symptoms of concussion or if participants were not medically cleared to participate in academic or athletic activities. The clinical symptom checklist was not a measure used for analysis, but was just a measure collected so that participants with undiagnosed concussions could be excluded from data collection. All participants were student-athletes who were currently participating in a club or varsity sport on campus. Seven of the participants played varsity football and twelve out of the fifteen participants self-identified as playing a contact or collision sport. Of the seven participants who played American-style Football, six wore the Riddell Speedflex helmet and one wore the Riddell

Speed Revolution helmet. None of the participants had been diagnosed with a concussion in the last 7-10 days prior to study participation. Five out of fifteen participants identified as Black or African American, eight participants identified as White, one participant identified as Hispanic, and two participants identified as Asian American. University student young adults ($N=15$; $M_{age}= 19.47$, $SD_{age}= 1.46$; 6 female, 9 male) completed this study either voluntarily or for academic credit in an Introduction to Psychology course at the College of William & Mary. All procedures performed in this study were in accordance with the Ethical Standards of the Institutional Protection of Human Subjects Committee. The results of concussion history survey questions are represented in Figure 1.

Apparatus and Stimuli

Participants were individually seated in front of a standard LCD monitor in a small, electrically shielded room. Participants were instructed to attend to a cue stimulus presented at the center of the monitor for 1000-1500ms. The cue stimulus was a Gaussian Gabor patch that spanned 200 pixels with a spatial frequency of .1 cycles per pixel. The cue varied in color (red or blue) and in orientation (0°, 45°, 90°, or 135°). The color and orientation of each cue stimulus was randomly selected on each trial and remained on-screen for a duration of 1000-1500ms. The cue stimulus was surrounded by either a white square or a white circle. Participants were instructed that the shape surrounding each cue indicated whether or not the cursor movement would be “normal” or “adapted”. Participants were also instructed that the color of the cue (red or blue) indicated its potential point value. One of the colors was assigned a low value of 5 points and the other color a value of 25 points. The assignment of shape to cursor movement type and the assignment of color to point value were constant within participants, but randomized across participants.

Following the cue duration, a blank screen appeared for 500ms and was then replaced by a fixation cross at the center of the monitor, which remained on-screen for a duration of 400-800ms. A target stimulus matching the cue and three distractor stimuli were then presented bilaterally. Participants were instructed to find the target stimulus that was the same as the cue and move the cursor (indicated by a small white circle) to its location on the monitor. The starting position of the cursor was 300 pixels up from the bottom center of the monitor. When the cursor reached any of the target stimuli, all four disappeared and corrective feedback was centrally presented for a duration of 500-1000ms. The corrective feedback included the word "Correct" or "Incorrect" printed in white above the number of points won or lost based on the participant's response and the running total of the points earned during the experiment. The next trial cue appeared after a blank inter-trial interval of 1000-1500ms. A schematic of the procedure is presented in Figure 2.

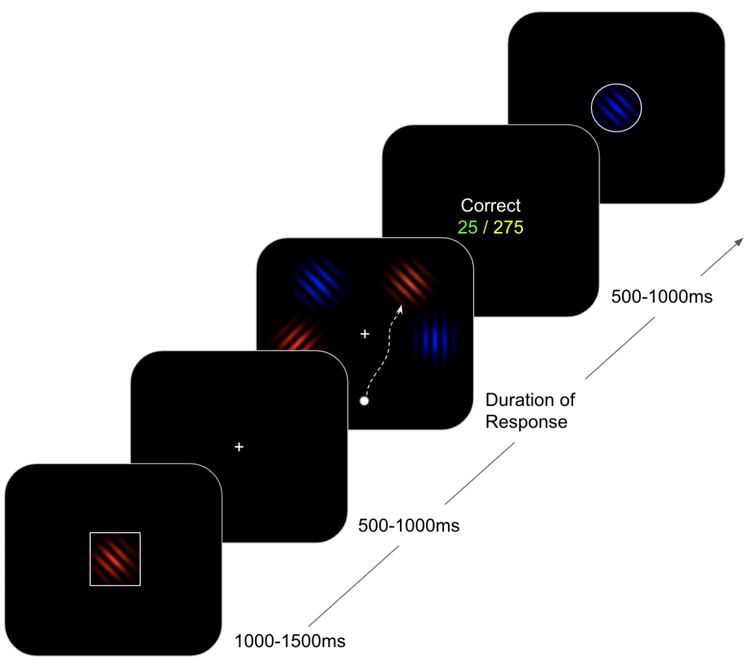

Figure 2. Schematic of the experimental procedure.

Degree of fluidity as a metric for describing the subjects' cursor movements will be observed in both "normal" trials in which the mouse will move as expected as well as "adapted" trials in which the participant will have to adapt to unexpected mouse movement in order to reach the target stimulus. Degree of fluidity of movement is a measure associated with normalized jerk.

Electrophysiological Recordings

Electrophysiological data were recorded continuously at 2000 samples per second using a DBPA-1 Sensorium bio-amplifier (Sensorium Inc., Charlotte, VT) with an analog high-pass filter of 0.01 Hz and a low-pass filter of 500 Hz (four-pole Bessel). Recordings were made using the 10-10 cap system with 72 Ag-AgCl sintered electrodes (Electrode Arrays, El Paso, TX) while participants were seated in an electrically shielded booth. EEG recordings were made using a forehead ground electrode and a reference at the tip of the nose. All impedances were adjusted to within 0-20 kilohms at the start of the recording session. EEG data were undersampled at 1000 Hz and analyzed offline using Brainstorm (Tadel et al., 2011). The data were corrected for ocular artifact using independent components analysis.

The EEG Data were then segmented between **[-200]**ms and **[1200]**ms with respect to stimulus and/or response onset. Segmented data were then averaged for each subject within each condition. ERP components were identified by inspection of the grand-averaged waveforms and mean amplitudes within the identified windows and were computed for each participant.

Results

A P3 component was identified in the grand average and measured between 250 and 600 ms at electrode Pz (see Figure 3). A low-impact group was identified as those participants who reported head impacts at a rate of four or fewer per week and a high-impact group was identified as those participants reporting five or more head impacts per week. P3 amplitudes were entered into a 2 (low-impact vs. high-impact) x 2 (switch vs. stay) x 2 (Normal vs. Adapted) repeated measures analysis of variance (ANOVA). The results of this analysis revealed only a three way interaction between Group, Switch Type, and Movement Type, $F(1,13)=11.89$, $p<.001$. In order to understand this interaction, the P3 amplitudes were entered into two 2 (low-impact vs. high-impact) x 2 (switch vs. stay) mixed measures ANOVAs separately for Normal and Adapted movement types.

For the normal movement trials, there was a significant main effect of group, $F(1,13)=6.11$, $p<.05$, $n^2=0.265$. Consistent with our hypothesis, the amplitude of the P3 component was significantly smaller in the high-impact group (M=4.41, SE=2.23) as compared to the low-impact group (M=12.0, SE=2.09).

For the adapted movement trials, the main effect of group only reached marginal significance, $F(1,13)=4.07$, $p= 0.065$, $n^2=0.203$, but the pattern of results was similar to those with normal movement and consistent with predictions (See figure 4). There was, however, a significant interaction between Group and Switch in the adapted trials, $F(1,13)=10.27$, $p<.01$, $n^2=0.060$, showing that only the high-impact group evidenced an increased P3 amplitude on Switch compared with Stay trials.

In order to better understand how these P3 differences are related to the number of reported head impacts, we examined the correlation between the magnitude of the difference in

P3 amplitude on Switch and Stay trials and the number of self-reported head impacts per week. Because of a dramatic positive skew in the number of self-reported head impacts, those data were log-transformed. The results of this analysis can be seen in Spearman's rank correlation which was computed to assess the relationship between the number of head impacts and the amplitude of the P3 component. There was a positive correlation between the two variables, r_s=0.66, n=15, $p < 0.05$.

To investigate the relationship between movement complexity and number of head impacts per week, a Pearson correlation was computed. There was no significant result, however results approached marginal significance, $r(15)=0.51$, $p=.051$.

Discussion

The purpose of this study was to investigate the relationship between sub-concussive head impacts and evoked electrical potentials elicited during a test of visuomotor adaptation. The purpose of this study was also to explore the relationship between sub-concussion and the behavioral measure of normalized jerk during a test of visuomotor adaptation. This study aimed to further the literature surrounding the use of ERPs and behavioral measures as potential supplemental tools for the detection of cognitive decline that can be associated with concussion or prolonged exposure to sub-concussive head impacts. The results of this study indicate a potential relationship between the number of head impacts an athlete experiences per week and a decreased p3 amplitude.

The findings of this study suggest that participants who experience a higher number of head impacts per week may experience greater difficulty with the higher cognitive demands associated with the "switch" trials of the study in which adapted cursor movements were required to reach the target stimulus. This result is reflected in the higher p3 amplitude seen in “switch” versus “stay” trials for individuals who have a higher number of head impacts per week within adapted trials (see Figure 4). Overall, the high-impact group consistently showed decreased p3 amplitudes as compared to the low-impact group, however, the high-impact group’s amplitudes sharply increased in their “switch” trials (see Figure 4 and Figure 5). The demand of task switching is consistently associated with switch costs which can be observed through increased p3 amplitudes (Kieffaber &Hetrick, 2005). It is also possible that the switch costs seen in the high-impact group are exacerbated by the cognitive impairment from which they may suffer on account of their high volume of experienced sub-concussions.

Compared to the dramatic switch costs seen in adaptive trials for the high impact group, in normal trials, this group showed almost no difference in p3 amplitude between “switch” and “stay” trials, however, their amplitude remained consistently suppressed as compared to the low impact group (see Figure 5). This result may be explained by the theory of selective resource allocation which is hypothesized to occur in individuals experiencing cognitive deficits associated with concussive or sub-concussive impacts (Ozen et al., 2013). Bryer et al. (2013) observed a similar phenomenon to this study in which they found that certain working memory tasks tend to elicit hyperactivation from subjects with a history of mTBI whereas other working memory tasks elicited a significantly decreased level of neural activation. Bryer et al. (2013) characterized these two types of working memory tasks as either “discrete” or “continuous”. A “continuous” task would be a task that requires a higher degree of executive control and requires context updating on behalf of the respondent. Bryer et al. (2013) used a meta-analysis of working memory studies of participants with a history of mTBI to conclude that “continuous” tasks elicit a pattern of hyperactivity and “discrete” tasks elicit decreased responses. The adapted trials of the current study may be viewed as “continuous” working memory tasks and this could explain the altered, increased activation pattern which was observed in participants in the higher impact group.

The findings of this study, with regard to the low-impact group, corroborate the previous findings of the task-switching literature. This is seen through the way that the p3 amplitude for the low-impact group for normal trials is higher in the “switch” versus “stay” trials. This increased activation is a well documented marker of the switch cost that is associated with this change (Kieffaber & Hetrick, 2005). As opposed to the switch costs which were observed through the p3 amplitude of the low-impact group in normal trials, the p3 amplitudes for the low-impact group in adapted trials were higher for “switch” trials versus “stay” trials. Overall, the difference between the amplitudes for this group for “switch” versus “stay” trials and so this slight difference may be a function of the small sample size of the study rather than a true effect of the task at hand.

There was no significant relationship between the number of head impacts per week and any of the measures of normalized jerk which were collected. Overall, the measure “ch-area” decreased for all participants over the course of the task. The measure “ch-area” is one of the measures of normalized jerk which was collected for this study and it is a measure in which a higher value represents a less fluid and direct cursor path towards the target stimulus. This result shows that “ch-area” and other measures of normalized jerk are useful measures of learning within this type of visuomotor adaptation task, however, they may not be effective measures or sensitive enough measures to detect the cognitive deficits associated with sub-concussions. It may be that this measure is not sensitive enough to detect the small differences that exist in populations of elite athletes experiencing sub-concussions. It may also be that this measure did not appear significant due to the small sample size of this particular study.

Previous literature has found significant decreases in P3 amplitude associated with collegiate athletes having a history of concussion (Brooks, 2016; Clayton et al, 2020; Dillon 2017; Gosselin et al, 2012; Hudac et al, 2018; Moore et al, 2017). The findings of the current study are consistent with the literature in that participant who reported more than five head impacts per week evidenced lower p3 amplitudes on average than the participants who reported only 0-4 head impacts in an average week of sports play and practice. This could potentially support the conclusions of previous literature from rodent models which showed decreased cognitive-motor performance associated with sub-concussions. However, it is imperative to note that the sample size of the current study was far too small to draw significant conclusions and it is also important to acknowledge that sports concussions are significantly underdiagnosed and therefore the cognitive decline seen in this population of athletes could be attributed to undiagnosed mTBI and not to sub-concussive impacts alone.

Future research should include much larger sample sizes and could benefit from recruiting participants from a lower number of different sports teams. This could allow the researcher to draw more meaningful conclusions because recruiting participants from a more specific subject pool could eliminate possibly confounding variables. Future research could also benefit from working in conjunction with a rodent model in which a rodent is given the number of sub-concussions that a specific athlete experiences and then both the rodent and human participant are tested on their cognitive-motor abilities. Future research could also benefit greatly from using more precise measures to quantify the number of sub-concussions that a participant experiences. Due to the limited scope of this project, this study relied on a self-reported measure of the number of sub-concussive impacts that a participant experienced in a week of practice and gameplay. Ideally, the researchers would be able to access film recordings from practice and games over the course of a season which could allow the researchers to more accurately assess the level of sub-concussion that a participant experienced. Future research could explore motivation and reward processing within an elite athlete population such as this and the way this may affect performance. This could also be enhanced through the manipulation of knowledge of results. Within the current task, participants were presented with an updated tally of their score at the end of every trial and it could be fruitful to explore if the motivation and overall accuracy are affected if the participants were not told of their score until the entire task was completed. Student-athletes are a population who have been conditioned over time to be highly point motivated through years of sport and it could also be promising to explore whether scores and motivation are affected if participants believe that their score will be reported to their coach or coaches.

The implications of this research on the overall well-being of student-athlete populations is significant because “an estimated 40,600 student-athletes have suicidal ideations each year” (De Olivers Martins, 2018, p. 6). It is important to highlight the mental health struggles of student-athletes because these individuals deserve to be seen and represented holistically. It is also significant to highlight that participation in collegiate sports is a risk factor for mental illness because of the positive relationship between mental illness and mild traumatic brain injury (Walz, 2008). Student-Athletes are a stigmatized group in higher education (Simons et al., 2007) and are frequently the subject of demeaning jokes and stereotypes related to their academic capabilities. This disadvantage is important to highlight because the experience of mild traumatic brain injury can negatively affect academic performance and compound the effects of stigmatization. A further implication of this study is the use of decoupled cognitive motor movements and the measure of normalized jerk as potential metrics for assessing cognitive motor function in elite athletes. The results of this study contribute to a rapidly growing body of literature and community of researchers urging institutions and the NCAA itself to increase their support of research into the long-term cognitive effects of prolonged participation in contact and collision sports.

The first limitation of this study was the overall clarity of the demographic survey which was used, in particular the question "For how many years have you been playing your sport at an organized level?". The purpose of this question was to determine for how many years the participant was likely to have been acquiring sub-concussive impacts related to their sport. Multiple participants believed that this question was asking how many years they had played their sport at the collegiate level. The second limitation of this study was the number of participants in the study. Due to the timespan of the data collection period and schedule constraints of all researchers and participants, this study was not able to collect data from as many participants as originally planned. This is a limitation because an inadequate number of data points prevents the researcher from drawing meaningful conclusions, regardless of the results of the study. This study was also limited because it was not feasible for each participant to participate in data collection twice over the course of the study. The original proposed design of the study intended for every participant to participate in the task twice because it would have allowed the researchers to track if amplitudes or behavioral measures were changed over the course of a season of collegiate sports. This would have allowed for much more easy comparison as well as a much larger data set from which to draw more meaningful conclusions. This study would have also benefited from conducting a handedness inventory and would also benefit from using a mouse that could be operated with one's left hand if a participant was left-handed.

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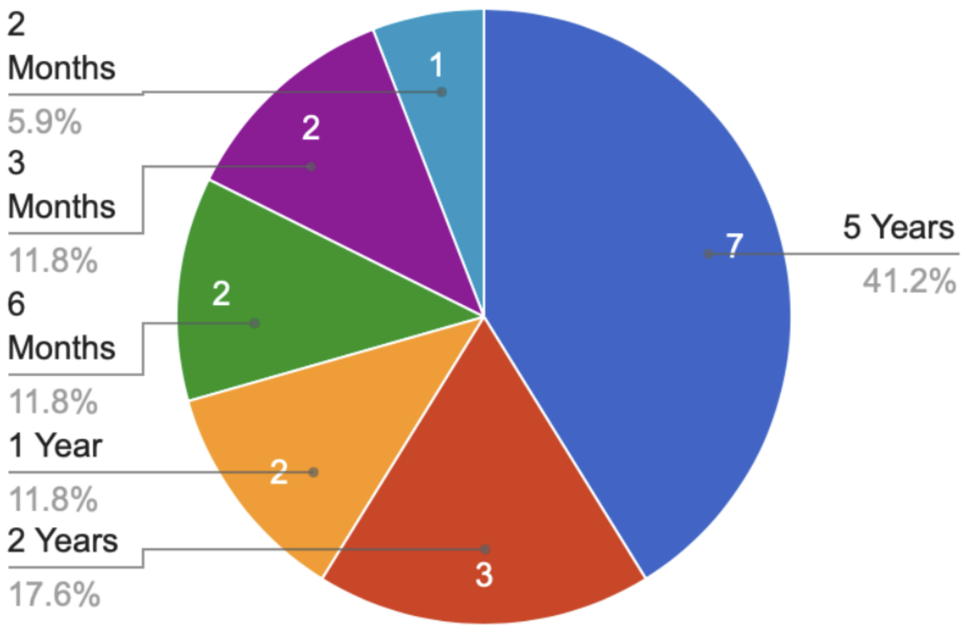

Figure 1. Number of Participants Reporting 1 Concussion Within Specific Time Intervals

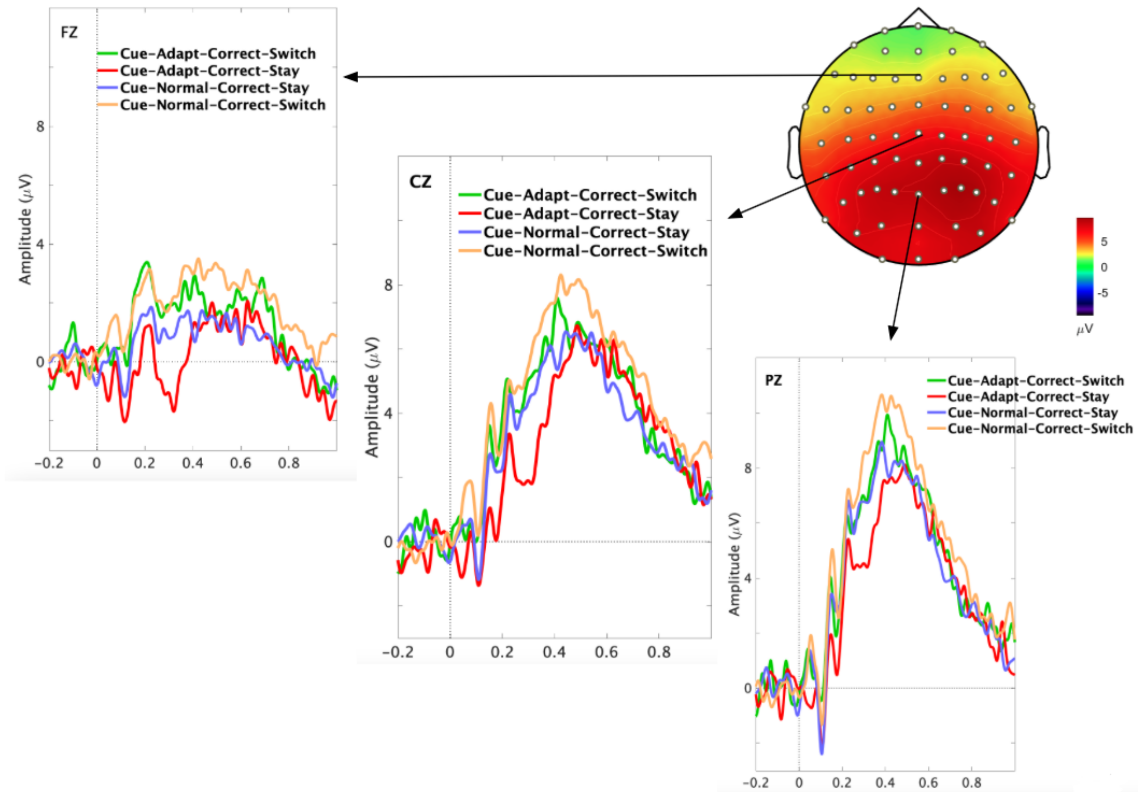

Figure 3. Midline P3 Component with Topography Grand-Averaged, Between 250-600 ms

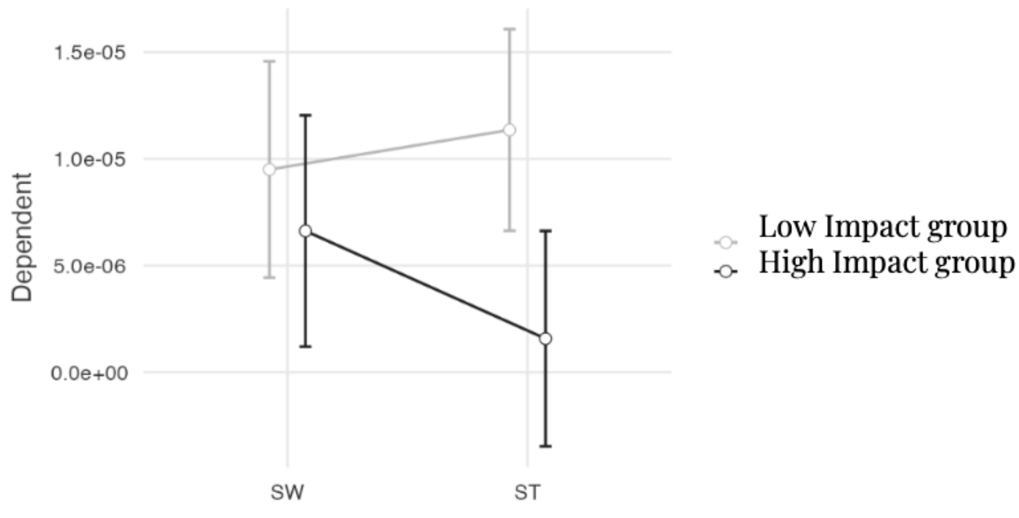

Figure 4. Estimated Marginal Means of Switch vs. Stay in "Adapted" Trials

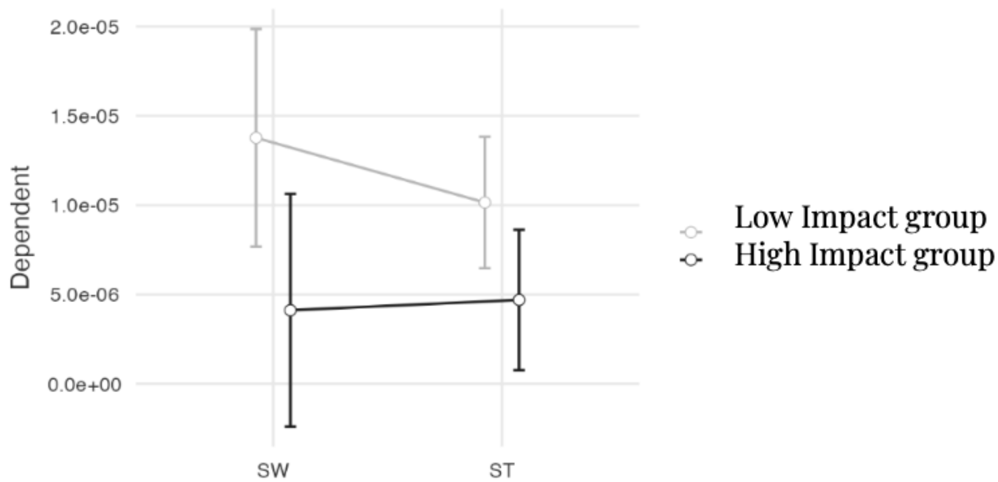

Figure 5. Estimated Marginal Means of Switch vs. Stay in "Normal" Trials