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Working Memory and Attention Deficits During a Letter Number Sequencing Task Post-Concussion

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Abstract

As the prevalence of sports related concussions rise, the long-term effects of concussions have garnered increasing research attention. Previous research has demonstrated that certain dimensions of executive function are especially susceptible to mild traumatic brain injury (mTBI), specifically working memory and attention. Previous studies using EEG have found that increased very low frequency oscillations (VLFO) disrupt goal-oriented activities and are associated with difficulties in cognition, hyperactivity and inattention in concussed individuals after mTBI. This study utilized continuous EEG during a letter number sequencing task on concussed and non-concussed individuals to assess deficits related to working memory and attention. It was hypothesized that concussed student athletes would display greater VLFO and decreased accuracy during the Millisecond Letter Number Sequencing Task. Results of this study showed evidence of a significant increase in the theta/beta ratio during the letter number reordering span in concussed individuals as well as shorter forward and overall span. This study allowed for the conclusion that concussed individuals show altered activity within the frontal lobe region during working memory tasks.

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Concussions are one of the most prevalent sports-related injuries today with approximately 2.5 million students from the US reporting having suffered at least one concussion within the year prior (Depadilla et al, 2018). One of the most common mechanisms for mTBI is from sports-related injuries, with an average annual incidence rate of 31.5 for every 100,000 individuals. Moreover, the most affected age range for these incidents is from 12-18 years old (Selassie et al, 2013). Yet both concussion diagnosis and treatment remain difficult for health care providers and coaches alike. Concussion diagnoses rely heavily upon self-identified and self-reported symptomology which may be easily hidden from health care providers and coaches in order to preserve the student's ability to play. Over 60% of first year college students reported engaging in play while still experiencing mTBI symptoms (Register-Mihalik et al, 2020). Likewise, 51% of US college students reported having suffered at least one concussion while on-campus student resource utilization was only 10%, exemplifying a possible misunderstanding of concussion severity and long-term impact (Meske et al, 2019). Prior to incident of concussion, over 80% of student athletes indicated that they intended to disclose to coaches or practitioners if they had suffered a concussion, yet less that 70% of students followed through (Register-Mihalik et al, 2020). The underutilization of on campus resources may be attributed to many social factors, including a concern for the increased duration of return to play protocol in college, a perceived lack of concussion severity, a mentality of pushing through any injury, and the uncertainty and apparent visibility of mTBI symptoms (Knievel et al, 2019).

While these concussions were once thought of as an inconsequential sport injury, they have since garnered increasing attention in both acute and long-term effects. The duration of symptomatology after suffering from a mTBI is variable. Acute effects of concussion are based upon concussion severity, ranging from mild to moderate to severe. Acute symptom range includes headache, confusion, lightheadedness, blurred vision, sleepiness, trouble with memory or attention, and sensitivity to light (Eunice Kennedy Shriver, 2018). Such symptoms typically resolve within a few weeks and are tested by use of the Post Concussive Scale (PCS). The PCS is a self-report scale with high internal consistent reliability, though women tend to report more symptoms than men when using this standardized scale (Lovell et al, 2006). The most common test used in pre and post-concussion testing is the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) computer-based test. Despite its recommended use for baseline testing to aid in return-to-play decision making, there is still heavy reliance on physical symptoms for return-to-play decision making. While 96% of athletic trainers indicated that they would not allow a symptomatic athlete to return to the field, only 86% indicated that they would not allow an athlete return to play if the ImPACT post-concussion test was below that of the baseline (Covassin et al, 2009). However, current research has indicated that invisible cognitive and emotional consequences remain, even for well-recovered individuals (Konrad, 2010).

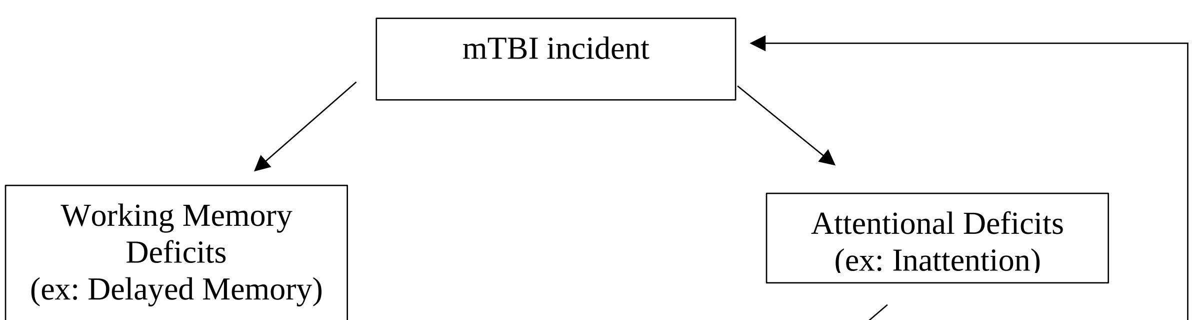
An interesting aspect to mTBI incidence is observation of certain differences in the type and extent to which deficits resulting from mild traumatic brain injuries (mTBI) affect each gender. It is possible that these differences may exist throughout many domains, including the number of concussions suffered, type, and severity which may result in long-term cognitive effects (Dick, 2009). While males report more significant cognitive symptoms, females report having higher numbers of sports-related concussion (Merritt et al, 2019). It is possible that the observed gender differences in symptom reporting could be due to female willingness to report symptoms mediated by self-image or societal pressures (Eiser et al, 1995). Specific cognitive symptoms that males have reported more frequently include amnesia, disorientation and confusion, whereas females reported increased drowsiness and sensitivity to noise (Frommer et al, 2011). However, other studies have found that females report more adverse post-concussion cognitive symptoms, even after correcting for differences in helmet use (Broshek et al, 2005). In culmination, further investigation is warranted due to the contradictory understanding of gender differences that arise post-concussion.

While acute mTBI symptom persistence is often relieved relatively quickly, it has been shown that executive function deficits linger (Skandsen et al, 2010). Both working memory and attention have shown to be two dimensions of executive function most impacted by mTBI. Specifically, individuals who have suffered a concussion exhibit worse auditory and visual working memory tasks (Keightley et al, 2014), possibly due to an inefficiency in resource recruitment for cognitive processing (Ozen et al, 2013). In an fMRI neuroimaging study, concussed individuals exhibited a decreased BOLD signal in the dorsolateral prefrontal cortex, the left premotor cortex, and left superior parietal lobe during both a verbal and non-verbal working memory task. Specifically, within the non-verbal task, concussed participants also showed decreases in task-related activity in the dorsal anterior cingulate cortex, the left thalamus and the left caudate nucleus. Results of this study indicated that dorsolateral prefrontal cortex activity is required for greater performance on verbal and non-verbal working memory tasks (Keightley et al, 2014). In a study utilizing an n-back test paired with EEG monitoring, concussed individuals displayed attenuated P300 activity, a wave associated with the cognitive process of categorization processes, and increased response times after stimulus presentation. This indicates that concussed individuals require greater time to respond to working memory stimuli due to a possible inefficiency in cognitive resource recruitment (Ozen et al, 2013).

Different stages of working memory have also been implicated in altered EEG coherence pattern when compared to non-concussed individuals, supporting the notion that working memory is especially susceptible to mTBI (Kumar et al, 2009). The working memory task consisted of verbal and visuo-spatial stimuli that required the participant to determine if the series of three presented stimuli coincided with the location of the novel cue. Despite concussed and non-concussed individuals displaying similar inter- and intra-hemispheric coherence during resting state, concussed individuals displayed poor intra-hemispheric coherence between the fronto-parietal and fronto-temporal regions during both the verbal and visuo-spatial tasks. Deficits included altered activity in the theta, alpha and beta bands (Kumar et al, 2009).

It has also been hypothesized that the orienting and executive networks of attention are particularly sensitive to mTBI (Halterman et al, 2005). Specifically, an inefficiency in allocating attentional resources has been implicated as an effect of mTBI, even three years post-injury (Broglio et al, 2009). Inefficient resource recruitment may also impact processing speed and accuracy in tasks with heavy demand upon attentional networks (Chan, 2001). It has been found that deficits in executive functioning and attention following completion of the Attentional Network Test and the Task-Switching Test may remain anywhere from 72 hours to 2 months after suffering from a concussion (Howell et al, 2013). It has been established that attentional deficits have long been implicated as a risk factor for suffering a concussion, as well as a common post-concussion symptom (Alosko et al, 2014; van Donkelaar et al, 2005). Increases in the theta/beta power ratio and length of response time during a goal-oriented task have also been associated with attentional relapses in concussed groups (Gazellini et al, 2016). It has been posited that attentional deficits may arise due to the observed susceptibility of the orienting and executive networks to mTBI (Howell et al, 2013). These attentional deficits can be further broken into more specificity. It has been found that young adults are especially susceptible to long term deficits in inhibition and divided attention, following multiple concussions (Bohnen et al, 1992). Additionally, these insufficiencies within attentional circuits have demonstrated that deficits in attention can lead to insufficiency in processing speed and accuracy (Bohnen et al, 1992; Chan, 2001).

Further studies have seen that the connection between attention and processing speed can further lead to difficulty in decision making and stress, further increasing the likelihood of suffering additional concussions (Wall et al, 2006). Further research is necessary to reveal the large-scale deficits in decision making that comes from suffering a TBI. However, a case study has found that after suffering from a TBI, there are impairments regarding decision making under several criterion such as handling an emergency, strategizing, and using information (Satish et al, 1999). These intertwining networks of symptoms have implicated the severity of this injury and the repercussions it may have, creating a recursive process of intial mTBI incident and resulting consequence (Figure 1).



In order to fully ascertain the residual neurocognitive effects within the body of research of mTBI, sensitive neuroimaging and neuropsychological tests must be employed. Neuropsychological assessments have historically been associated with management of concussions. The validity and accuracy of varying neuropsychological tests have long been questioned, with a great amount of research aimed at determining the best standardized battery of tests in assessing long term consequences of mTBI (Moore et al, 2018). The Repeatable Battery for the Assessment of Neuropsychological Status (RBANS) is one such test that measures cognitive ability and neuropsychological status. The RBANS is often a measure used to assess particular components of executive functioning in concussed and non-concussed individuals (Strauss et al, 2006).

The use of electroencephalogram neuroimaging techniques has demonstrated to be an efficient and inexpensive tool in assessing executive functioning symptom persistence of mTBI (Munia et al, 2017; Kumar et al, 2009). An example of a useful test to conduct during the continuous EEG paradigm was the Color Word Interreference Test (CWIT) of the Delis-Kaplan Executive Function System (DKEFS). The CWIT is comprised of four subtests, two of which evaluate the participant's inhibition and inhibition task switching ability. The inhibition specific task is comprised of color words, such as red, printed in opposing ink colors, such as blue. The participant must say the ink color and inhibit reading the word. The inhibition task switching followed a similar paradigm, expect for when the word is within a box. In this case, the participant must switch to reading the word itself and inhibiting the ink color. This task is one of the most widely used subtests of the DKEFS for evaluation of executive function and processing speed. Within control populations and TBI populations, the CWIT has proven to remain consistent in the validity of its standardization by age and cut-off values, further supporting its value in assessing executive function deficits in the mTBI population (Eglit et al, 2019).

Further EEG specific findings focus on the relative ratio of very low frequency oscillations (VLFO) and the default mode network (DMN). The DMN is a baseline level of VLFO activity associated with introspective mental activity. When attention shifts to an extrospective task, the DMN is attenuated, allowing for proper task completion. The more difficult a task, the greater the attenuation should be (Fransson, 2005). Many ADHD studies have shown that lapses in VLFO attenuation is linked with inattention and overactivation of the posterior cingulate cortex and the dorsolateral prefrontal cortex as well as the parietal lobe

(Weissman et al, 2006; Helps et al, 2009). Studies in the efficacy of neurofeedback training has also contributed to the understanding of DMN activation. It has been shown that participants who decrease the ratio of theta/beta activity while utilizing neurofeedback techniques have displayed gains in consequential attention functioning (Linden et al, 1996; Monastra et al, 2006). Thus, the Default Mode Interference (DMI) hypothesis, the situation in which lapses in attention during a goal-oriented activity corresponds with increased DMN activity, was established (Sonuga-Barke & Castellanos, 2007). It is reasonable to posit that similar VLFO and DMN inactivation may be observed in participants with attentional deficits post-concussion. Despite the differing etiology of inattention, the brain regions affected in ADHD overlap with commonly injured regions due to mTBI, specifically the prefrontal cortex (Gazellini et al, 2012).

The test paired with the continuous EEG paradigm in the current study was the Letter Number Sequencing Task (LNS). The LNS is commonly utilized as an assessment of working memory (Egeland, 2015). The task requires the individual to hold a span of letters and numbers in their working memory, and then reorder the numbers in ascending order and letters in alphabetical order, in increasing difficulty. Digit span abilities are associated with working memory storage, while letter-number reordering tasks is able to show evidence of manipulation deficits within individuals during the task (Egeland, 2015). Previous research has shown that adults with severe TBIs performed significantly slower on LNS tasks (Kennedy et al., 2009). However, LNS remains a promising cognitive test that has not yet been used to assess effects post-concussion as it has been shown to activate brain areas associated with working memory and attention (Barlow et al, 2018). Thus, the current study combined the use of continuous EEG neuroimaging while completing the LNS task in order to quantify the long-term effects of mTBI on attention and working memory. It was hypothesized that individuals who have suffered a concussion would demonstrate shorter LNS span and poorer accuracy as well as altered brain wave while completing the task when compared to controls.

Method

Participants

Participants were recruited from introductory psychology courses at Ursinus College with course credit as their incentive for participation. Students of any status were encouraged to participate. Participants (N = 59) included self-identified concussed and non-concussed individuals. The concussed group consisted of 22 subjects with ages ranging from 18-21 (M = 19.18, SD = 0.95). The non-concussed group consisted of 37 subjects ages 18-21 (M = 19.48, SD = 1.26) (Table 1). All participants received informed consent prior to testing and all procedures were approved by the Ursinus College Institutional Review Board prior to completion of the study.

Procedure

Participants completed a demographic questionnaire including age, gender, athletic status, Attentional Deficit (ADD/ADHD) diagnosis and concussion status. If applicable, participants were asked about symptom persistence.

The Barkley Deficits in Executive Functioning Scale (BDEFS-LF) was used to assess dimensions of executive functioning. The BDEFS is comprised of 89 items including problems experienced post-concussion and ADHD specific items (Barkley, 2001). Each item is based on a Likert-type scale ranging from 1 (never or rarely) to 4 (very often) that best describes behavior relative to the last 6 months. Three indices were assessed; the total scores for executive function (EF), ADHD-EF index, and the EF symptom count. The total scores for executive function included the overall sum of the 5 subsections within the questionnaire. The five subsections include reporting on self-management, self-organization, self-restraint, self-motivation and self-regulation of emotion. The higher the sum of the 5 subsections the increased probability of exhibiting deficits in executive functioning within daily activities. The ADHD-EF index is measured by adding together 11 specific items on the report that are specific to identifying symptomology of ADHD. Generally, a score of 20 or higher indicates an individual with ADHD. Lastly, the EF symptom count measures the rare responses of 3(often) and 4 (very often) as evidence for executive functioning deficits. The higher the sum of rare responses the greater possibility of the EF deficits.

While under continuous Biopac EEG analysis, the Millisecond Letter Number Sequencing task retrieved from Inquisit was completed. This consisted of one auditory forward span trial and one recoding span trial in a randomized order. Both trials of the Inquisit Letter Number Sequencing Tasks were almost identical to the WAIS Letter-Number Sequencing Test (Egeland 2015), except for the inclusion of the backward span condition. Participants were prompted to complete a practice trial for each condition prior to actual scored task and start of the EEG recording. The forward span task completed in this study required the participant to type the letter and number sequence exactly as it was heard. The first sequence of letters and numbers presented began with two numbers and increased the span of numbers as the participant continued through the task. The reordering (letter number sequencing) trial required the participant to place the numbers in ascending order and the letters in alphabetical order after they heard a randomized sequence from the computer program. The first sequence presented used only two letters/numbers and increased the span as the task was continued. Total scores for each condition were recorded from the data report computed by Inquisit.

Continuous EEG data was scored using ten second intervals within the first and last minute of each trial. Power values for each frequency band was averaged for each condition to create a composite EEG score. For band base analysis, EEG was divided into traditional frequency bands using fast Fourier transform for each condition of Letter Number Sequencing Test (LNF = letter number forward span and LNR = letter number reordering span).

Prior to completion of the Letter Number Sequencing Task, participants were asked to sit with their eyes closed for 20 seconds with minimal thought and no movement while under continuous EEG monitoring in order to ascertain a basis for individual brain activity. This was followed by 20 seconds of eyes open, and a second iteration of eyes closed. This data was used as a control in EEG data analysis.

Results

Participants

A total of 59 participants were tested: 22 were classified as previously concussed individuals and 37 as non-concussed individuals. Demographic information is presented in Table 1. Average time since last concussion was 45.91 months. All students were recruited from an Introductory Psychology course and provided written informed consent before participating within the current study.

Table 1. Demographic information in concussed and non-concussed groups.

Concussion Status	Participants	Age	Months Since Concussion

Concussed	N = 22	M = 19.18 SD = 0.95	M = 45.91 SD = 33.27
Non-concussed	N = 37	M = 19.48 SD = 1.26	N/A

Concussed Individuals Perform Worse on Working Memory Task

It was expected that concussed individuals would exhibit behavioral deficits in both LNF, LNR and overall LNS task completion. Independent sample t-tests were conducted. Concussed individuals (M = 12.04, SD = 2.78) held a shorter total points LNF span than non-concussed (M = 14.03, SD = 2.56), $t(57) = 2.77$, p = .001 (Fig. 2). A trend for LNR accuracy was observed in which concussed individuals (M = 9.95, SD = 2.86) held a shorter span than non-concussed individuals (M = 11.48, SD = 9.95), $t(57) = 1.93$, p = .058. However, upon combining the two for total LNS completion, concussed individuals (M = 22.00, SD = 4.74) still exhibited decreased performance when compared to non-concussed (M = 25.51, SD = 4.78; Fig. 3), $t(57) = 2.73$, p = .008. It was also hypothesized that individuals with a history of concussion would exhibit altered brain wave activity during completion of the LNF and LNR task. An independent samples t-test revealed that concussed individuals have an elevated theta/beta ratio (M = 2.35, SD = 1.36) when compared to non-concussed (M = 1.71, SD = 1.04) during the LNR task only, $t(57) = 1.12$, p = .04 (Figure 4).

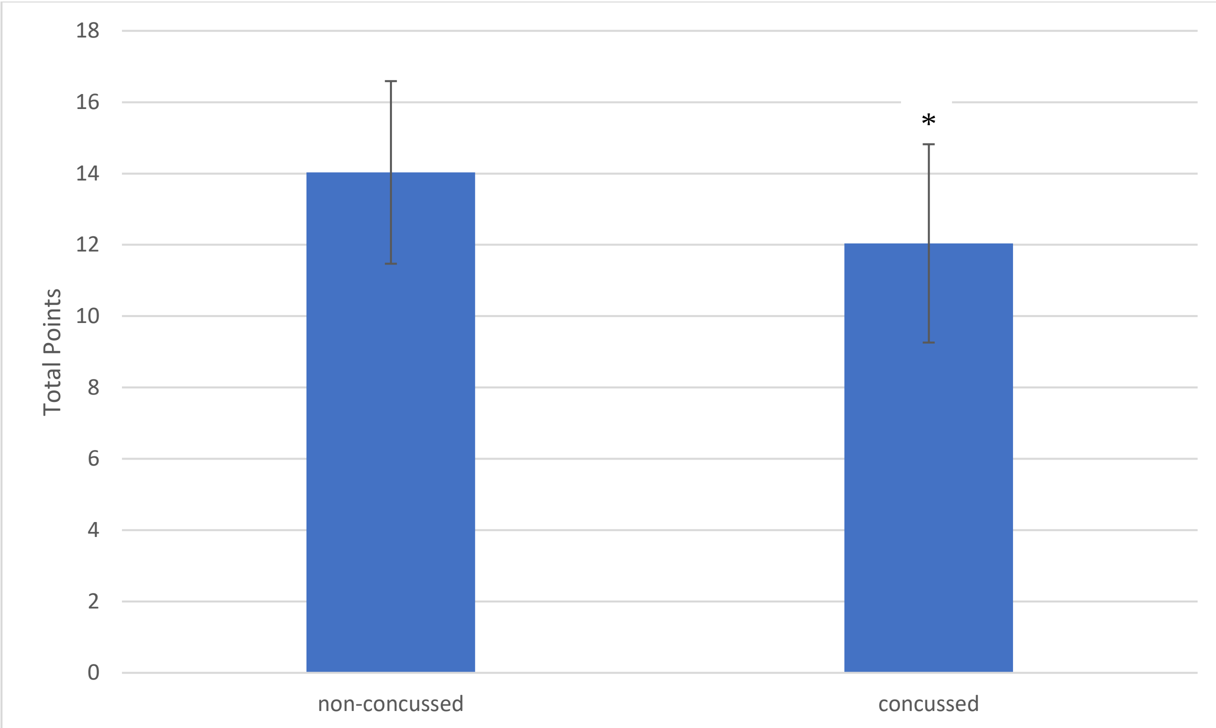


Figure 2. Concussed individuals exhibit decreased accuracy in forward span recall. Concussed and non-concussed participants were given three trials of each increasing span size. If the participant failed twice, the test was concluded. Total points indicate advancement in the task. Concussed individuals performed significantly worse. * $p = .001$.

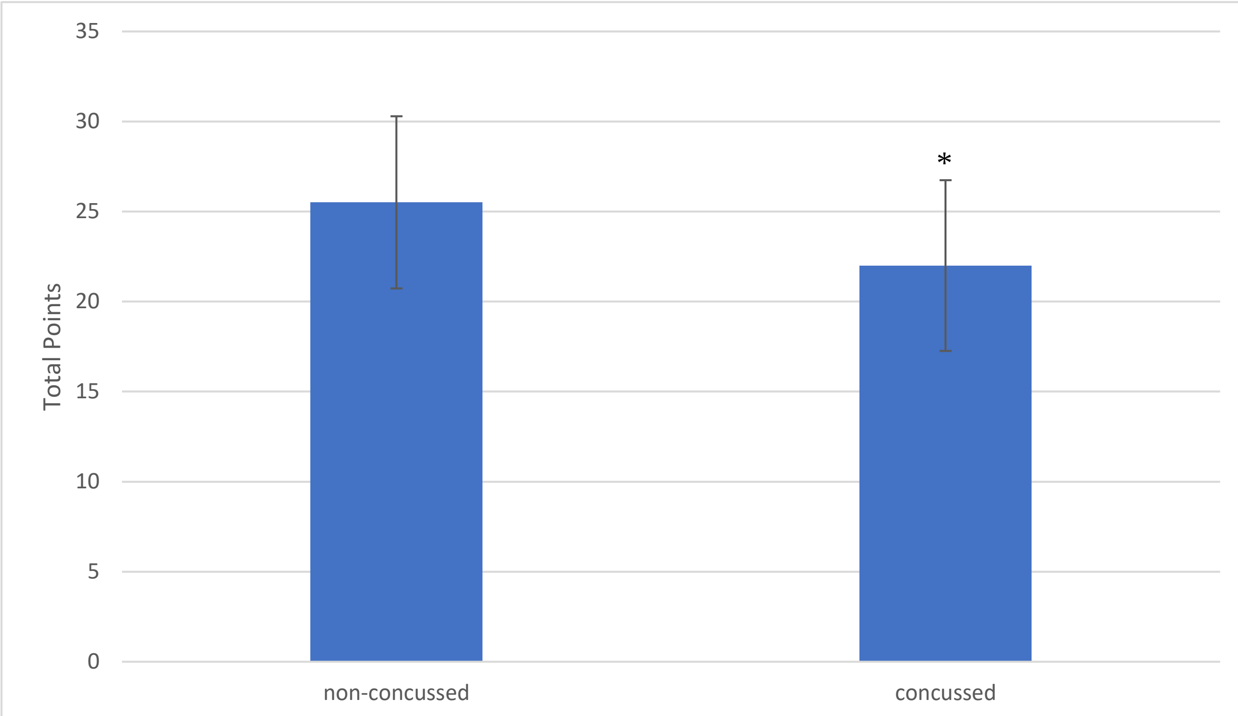


Figure 3. Concussed individuals performed worse on the letter number sequence task. Concussed and non-concussed participants were given three trials of each increasing span size for a letter number forward and letter number reordering condition. If the participant failed twice, the test was concluded. Total points indicate advancement into each task and combined to calculate total LNS completion. Concussed individuals performed significantly worse than non-concussed individuals. *p = .008.

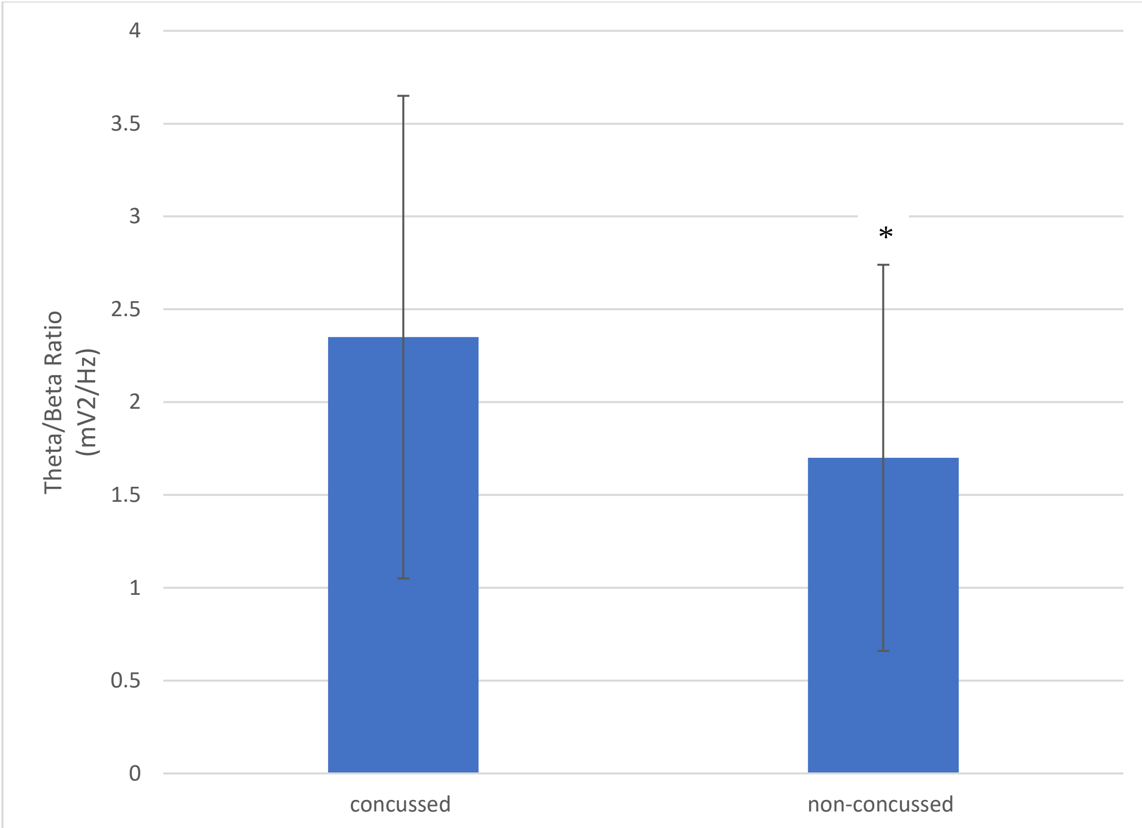


Figure 4. Elevated theta/beta ratio in concussed individuals during letter number reordering task. While under continuous EEG, participants were tasked with the reordering condition of the Letter Number Sequencing task. EEG readings were analyzed by obtaining an average area of alpha, beta, theta, and delta waves. Error bars represent the standard error of the mean. $*p < 0.04$

Lack of VLFO Attenuation in Concussed Participants

Pearson correlations were conducted to determine if there was an interaction between behavioral results and theta/beta ratios. There was a significant correlation between LNR total points and the corresponding LNR theta/beta ration in non-concussed participants, indicating that reduced theta/beta ratio is a predictor for LNR performance, $r = -0.34$, $p = .04$ (Figure 5). However, the same correlation did not reach significance in concussed individuals, indicating that the theta/beta ratio is no longer predictive of LNR performance, $r = 0.2$, $p > .05$ (Figure 6).

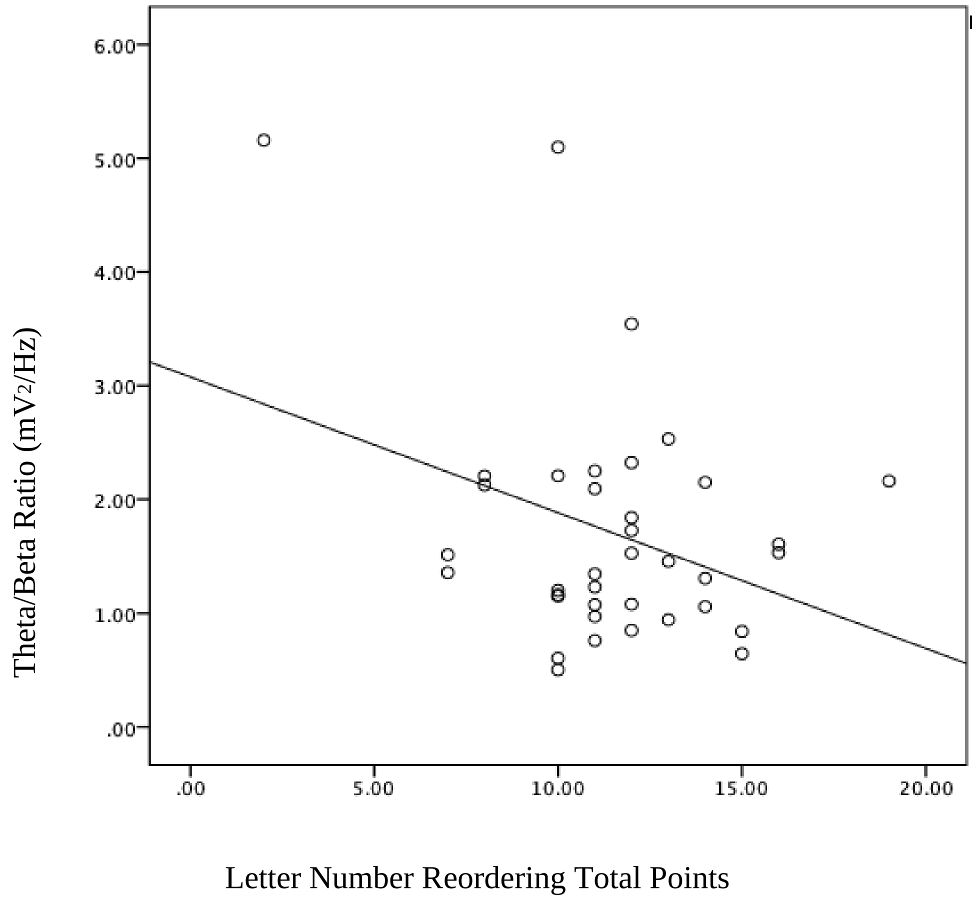


Figure 5. Inverse relationship between theta/beta ratio and reordering performance in non-concussed individuals. Participants were tasked with reordering a random string of numbers and letters into ascending numerical order and alphabetical order while under continuous EEG monitoring. Greater attenuation of the very low frequency oscillations resulted in greater letter number task performance for individuals with no history of concussion, $r = -0.34$, p = .04.

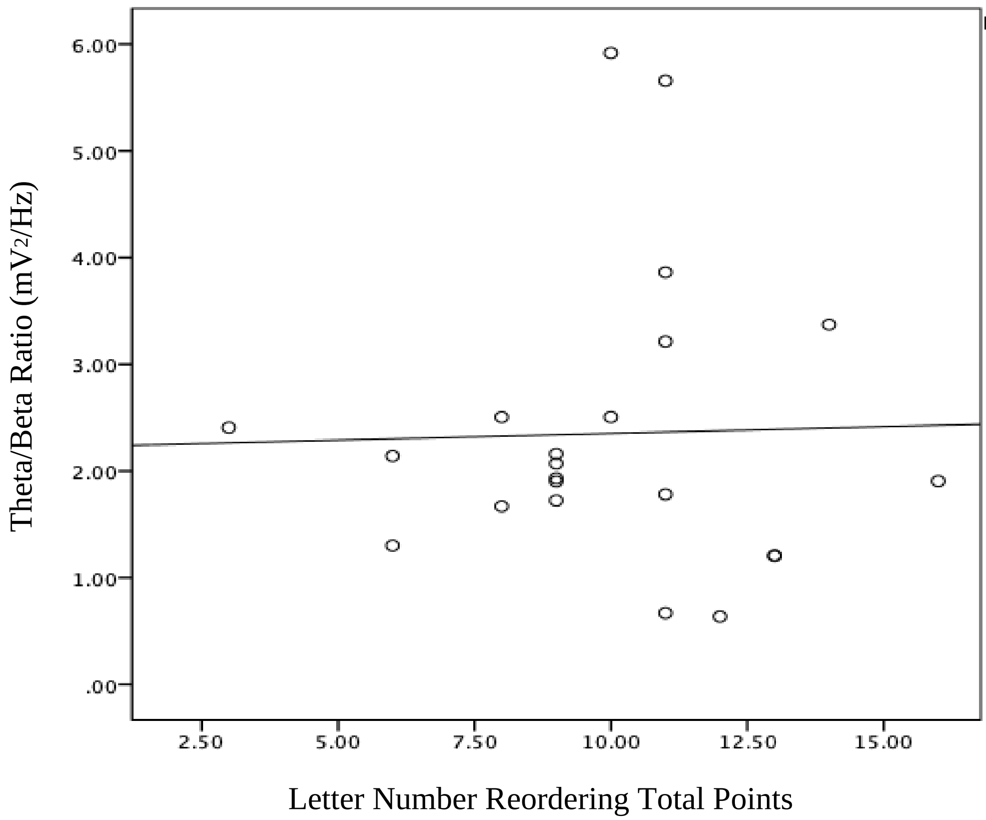


Figure 6. No relationship between theta/beta ratio and reordering performance in concussed individuals. Participants were tasked with reordering a random string of numbers and letters into ascending numerical order and alphabetical order while under continuous EEG monitoring. There was no observed attenuation of the very low frequency oscillations for any performance level, $r = 0.2$, $p > .05$.

Discussion

It was expected that concussed individuals would exhibit shorter spans in all conditions of the LNS task. While there was no behavioral difference between concussed and non-concussed individuals for reordering, concussed participants performed significantly worse at both the LNF and overall LNS task up to 45 months post-injury. Current results corroborate with the existing literature, as many other mTBI studies have found similar results. Specifically, concussed individuals displayed a similar inability to activate and modulate working memory during increasing difficulty of an n-back test. In fact, concussed participants displayed greater activation during the 1-back and 2-back tasks yet less increase for the more difficult 3-back task, indicating an inability to match processing resources with task demand (McAllister et al, 2006). This offers a possible explanation as to why the current sample displayed significantly worse completion for the forward span but not for the reordering span; concussed individuals may have overcompensated in resource recruitment for the simpler task but not for the more challenging reordering task. This holds important implications for both working memory and attentional ability for collegiate athletes as multiple concussions will likely exacerbate this effect, causing worsening symptoms.

It is well known within the mTBI literature that multiple concussions create a cumulative effect. With each additional concussion, symptoms persistence and severity worsen in both acute and long-term effects. In a study comparing the acute effects of multiple concussions, amateur athletes with multiple concussions scored significantly lower on a verbal and working memory task (Iverson et al, 2004). Athletes with multiple concussions were also 7.7 times more likely to demonstrate a significant drop in memory performance compared to no athletes who have not suffered a concussion. (Iverson et al, 2004). In a meta-analysis of the long-term effects after multiple self-reported concussions, the overall effect on neuropsychological performance across seven domains was minimal. However, upon investigating the domains individually, poor performance in executive function, delayed memory and language was associated with multiple concussions (Belanger et al, 2009). Essentially, the literature indicates that the greater amount of concussion an individual suffers, the greater the symptom severity will be, impacting aspects of executive function, working memory and attention. It has also been demonstrated that individuals who display executive functioning and attentional deficits are more likely to engage in risky play and behavior that may lead to a concussion, thus creating a cycle of mTBI effects resulting in increased mTBI incident (Wall et al, 2006). Given that the current study found evidence of long-term effects of concussion up to four years later, the susceptibility of falling within this cycle goes far beyond the immediately visible symptoms of mTBI. In fact, this study indicates that the long-term residual effects of concussion, up to at least four years post initial injury, are the same effects that have been implicated within this cycle.

EEG analysis proved sensitive to VLFO activity. The observed theta/beta ratio was significantly increased in concussed participants compared to non-concussed participants, indicating that concussed individuals were unable to properly mediate the switch between DMN and extrospective task orientation. This also supports the notion that the executive component of working memory, specifically the ability to allocate and modulate resources, is negatively impacted after a concussion. Similar results were found in a study which paired the Erikson-Flanker Test with continuous EEG monitoring. It was found that TBI participants displayed higher theta/beta ratios and decreased accuracy and reaction time during task completion when compared to the healthy controls (Gazzellini et al, 2016). Both studies support inappropriate recruitment of resources, as was also previously demonstrated in a similar study (Chan, 2001). Current results also coincide with preexisting literature as made evident by the frequency of elevated theta power during varied executive function related tasks (McCrea et al, 2010; Scheeringa et al, 2009; Munia et al, 2017).

It was also hypothesized that the default mode interference hypothesis would account for any interaction between inappropriate VLFO and resulting impaired behavior. Results indicated that while non-concussed participants displayed a significant negative relationship between theta/beta activity and span, concussed individuals did not. This indicates that inactivation of

VLFO is necessary for proper resource recruitment and attention for task completion. However, as non-concussed participants did not display this same relationship, it is likely that mTBI injury interferes with VLFO regulation. Similar studies have indicated that inappropriate elevation of theta/beta power is positively correlated with inattention (Putman et al, 2014; Weissman et al, 2006). Likewise, an inability to attenuate VLFO corresponds with increased attention deficits and increased reaction times (Helps et al, 2009). Interestingly, other studies have found an increase in beta power in conjunction with significantly less theta band activity over the frontal lobe for concussed individuals could provide a possible compensation mechanism for cognitive deficits that may arise post-concussion (Balkan et al, 2015). Ultimately, further research in the changes in brain wave activity post-concussion is required to further elucidate the long-term effects of mTBI.

One of the most commonly used tests after suffering a concussion is the immediate post-concussion assessment and cognitive testing (ImPACT). The ImPACT is a computerized test that measures attention, memory, reaction time, processing speed, and post concussive symptoms (Nebraska, 2016). In recent years, the validity of the ImPACT test's ability to evaluate cognitive deficits have been a subject of debate. A meta-analysis of over 5,000 studies utilizing the ImPACT have found discrepancies in both validity and accuracy of its diagnostic and predictive capability. Researchers believe that clinicians must individualize analysis of the test for each patient (Alsalaheen et al, 2016). The ImPACT is only sufficient for testing deficits immediately after a known concussion has taken place. However, the current study has demonstrated that future use of EEG in both on and off-site testing environments could be a viable option for assessing both acute and long-term effects in post-concussion symptom persistence, given further research. The development of a standardized EEG assessment that compares baseline to post-concussion would offer great clinical utility.

While trends for lower scores for reordering span was observed in the current scope of this study, it failed to reach significance. With more time and an increased sample size, it is reasonable to posit that this trend may continue, and that more statistically significant behavioral differences may arise. Likewise, increasing sample size would decrease the variability within the concussed participant group, allowing for a clearer understanding of the interaction between theta/beta activity and resulting behavioral in concussed participants. In addition to garnering a larger sample size, future iterations of the LNS use would benefit from an alternative administration method than Inquisit. There was no issue with physical data collection or trials, but test administration and practice trials held glitches that were unable to be fixed. Thus, it is recommended to use an alternative online or in person platform for administration of the battery to ensure a smooth testing session. Utilizing a pre and post-test design would also offer greater insight into the long-term effects of concussions. An ideal study would include pre-season baseline EEG testing that assess vulnerable dimensions of executive function, specifically working memory and attention. Such as assessment would aid in determine both athlete susceptibility to concussion as well as symptom severity and persistence after concussion incident.

Despite these present issues, the current study has resulted in promising results and a viable technique in evaluating differences between those concussed and non-concussed. As EEG systems are affordable and easily accessible, future directions for evaluating the long-term effects of mTBI would benefit from continual pairing of EEG recording during executive function tasks. Such tasks can be expanded beyond the LNS utilized in the current design.

Neuropsychological tests to include should relate to not only working memory, but attention, cognitive flexibility and impulse control. Likewise, future studies would benefit in breaking down individual aspects of executive function, such as working memory, into its own multiple facts. For example, the current study is unable to differentiate between the executive component and the storage component of working memory. Further modifications to the current study design could include differentiating between visual and auditory working memory. The current design presented the participants with the string of numbers and letters out loud, thus only testing the auditory aspect of working memory. A simple addition to this test would be to present the string of numbers and letters visually, such as one digit presented at a time on a screen for a standardized duration, before asking the participant to repeat both the forward and reordering span. Likewise, with an increased sample size, it would be beneficial to investigate the impact of multiple concussions on working memory performance. Analyzing the performance between students who have not suffered a concussion, those who have suffered one concussion, and those who have suffered more than one concussion would further inform the literature as to the extent of possible cumulative, long-term effects of mTBI. Ultimately, increasing the specificity of the empirical design will allow for greater understanding in the exact underpinnings of the long-term effects of mTBI on executive function. Further research into the specific neurological underpinnings and symptom persistence of mTBI visible by EEG could potentially aid in creation of a non-biased diagnostic design, lending EEG as a powerful yet inexpensive clinical tool.

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