Elevated Delta and Theta Waves During Letter Number Reordering Tasks in Concussed Individuals

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As the prevalence of sports related concussions rises, 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, or mTBI, specifically working memory and attention. Previous studies using electroencephalogram (EEG) have found that increased delta and theta frequencies are associated with difficulties in cognition, hyperactivity and learning deficits in concussed individuals after mTBI. This study utilized continuous EEG during a letter number sequencing task on concussed and non-concussed individuals to assess possible deficits related to working memory. It was hypothesized that concussed student athletes would display abnormal EEG wave patterns during the Millisecond Letter Number Sequencing Task as a result of the long-term consequences associated with mTBI. Results of this study showed evidence of a significant increase in both the delta and theta waves in concussed individuals during completion of the letter number reordering span task. This study allowed for the conclusion that concussed individuals showed altered activity within the frontal lobe region during working memory tasks in the form of elevated delta and theta waves resulting from hyperactivity of various brain circuits involved in the complex working memory network. Different brain regions may have been working harder to recruit the resources necessary for completion of the LNS tasks, as a result of the consequences of the brain injury. Further research is required to describe the major cognitive resources lost due to concussion and to specify the circuits exhibiting hyperactivity.

Abbreviations: DLPFC – Dorsal Lateral Prefrontal Cortex; EEG – Electroencephalogram; LNF – Letter Number Forward Task; LNR – Letter Number Reordering Task; LNS – Letter Number Sequencing Task; mTBI – Mild Traumatic Brain Injury

Key Words: Concussion; Delta-Waves; Theta-Waves; Letter-Number-Task; Working Memory; Attention; Executive-Function

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Introduction

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). 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. Acute effects of concussions are based upon concussion severity, ranging from mild to moderate to severe, and typically resolve within a few weeks, depending upon severity. Concussions, or mild traumatic brain injuries (mTBI), can be identified through symptoms such as headaches, confusion, lightheadedness, trouble with memory and attention, among others (Konrad, 2010).

While acute mTBI symptoms 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 (Curtis & D'Esposito, 2003). Specifically, individuals who have suffered a concussion exhibit worse auditory and visual working memory ability (Keightley et al., 2014), possibly due to an inefficiency in resource recruitment for cognitive processing (Ozen et al., 2013). Evidence of inefficient recruitment of resources can be seen through brain imaging patterns that portray hyperactivity.

In order to fully ascertain the residual neurocognitive effects of mTBI, sensitive neuroimaging and neuropsychological tests must be employed, such as EEG. This type of neuroimaging 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). EEGs measures electrical activity within the brain through the recording of various brain wave patterns (alpha, beta, delta, and theta). Abnormal patterns of these brain waves could be evidence of various cognitive deficits depending on which waves are exhibiting abnormal electrical signals. Delta and theta waves are slower brain waves that when elevated, provide indication of hyperactivity in brain function, indicating a possible learning or attentional deficit (Demos, 2005; Munia et al., 2017).

Previous studies have investigated the different stages of the working memory process through altered EEG coherence patterns when compared to non-concussed individuals, supporting the notion that working memory is especially susceptible to mTBI (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), which could lead to deficits in learning and working memory tasks. Past research has observed 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), which can be shown through abnormal EEG wave averages. For example, increases in delta and theta frequencies, along with decreases in beta frequencies among concussed individuals has been found in previous research (McCrae et al., 2010; Munia et al., 2017).

Continuous EEG paradigms are often paired with executive function-demanding neuropsychological tests. Digit span abilities are associated with working memory storage, while the letter-number reordering tasks have previously shown evidence of manipulation deficits within individuals during completion of the task (Egeland, 2015; Barlow et al., 2018). Thus, the current study combined the use of continuous EEG neuroimaging while completing the WAIS-IV Letter Number Sequencing (LNS) Tasks in order to quantify the long-term effects of mTBI on attention and working memory, and more generally, executive function. The LNS task utilized in this study, requires the individual to hold a span of letters and numbers in their working memory and retrieve them during the forward span task. Additionally, the reordering portion of the task involves the retrieval and reordering of the numbers into an ascending order followed by the letters in alphabetical order, in increasing forms of difficulty. While other LNS tasks may focus on speed of task completion to assess processing speed, the current study relied upon total span accuracy as a means to measure working memory.

Previous research has shown that adults with severe TBIs performed significantly slower on LNS tasks (Kennedy et al., 2009). However, the WAIS-IV LNS task is a promising cognitive test that has not yet been used to assess effects post-mTBI or when combined with EEG neuroimaging. Thus, the current study will provide insight into measurement of the deficits associated with the long-term, post-concussive cognitive consequences on attention and working memory. It was hypothesized that individuals who have suffered a concussion would demonstrate shorter WAIS-IV LNS span and poorer accuracy, as well as abnormal EEG wave patterns during completion of the task.

Materials and Methods

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 = 29) included self-identified concussed and non-concussed individuals. The concussed group consisted of 13 subjects with ages ranging from 18-21 (M = 19.54, SD = 1.20). The non-concussed group consisted of 16 subjects ages 18-21 (M = 19.56, SD = 1.09) (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.

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

Concussion Status	Subjects	Gender	Age	Months Since Concussion
Concussed	N = 13	Male = 8 Female = 5	M = 19.54 SD = 1.20	M = 49.33 SD = 38.63
Non-concussed	N = 16	Male = 8 Female = 8	M = 19.56 SD = 1.09	N/A

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.

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 10 s intervals within the first and last minute of each trial. Power values for each frequency band were 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 = forward span task and LNR = letter number sequencing task).

Results

A total of 29 participants were tested: 13 were classified as previously concussed individuals and 16 as non-concussed individuals (Table 1). An independent samples *t*-test was conducted to examine the differences between groups for behavioral results and EEG recordings. ADHD diagnosis data was not included in this study's analysis of results, as only two participants reported diagnoses.

It was expected that concussed individuals tasked with a letter number sequencing task would display altered brain activity compared to non-concussed individuals while under continuous EEG. Though there was no difference in delta waves between concussed and non-concussed individuals (concussed, M = 161.99, SD = 48.55; non-concussed, M = 163.83, SD = 84.38) for the forward span condition, concussed individuals (M = 209.56, SD = 99.14) displayed significantly greater delta waves during the letter number reordering condition when compared to the non-concussed individuals (M = 138.84, SD = 49.37), $t(17) = -2.33$, $p = 0.032$ (see Figure 1).

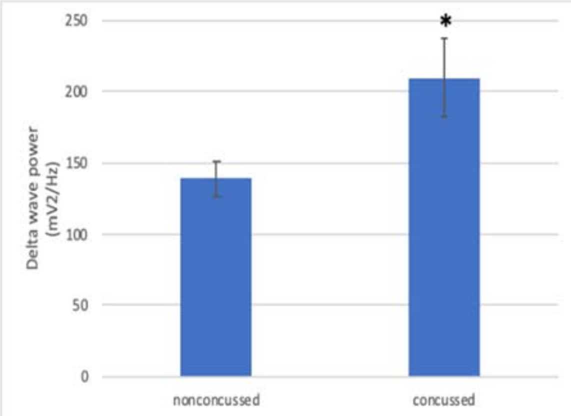

Figure 1. Increased delta wave power in concussed individuals during letter number reordering task. While under continuous EEG, participants were tasked with the reordering condition of the Letter Number Sequencing task. EEG readings were analyzed by obtaining an average area of alpha, beta, theta, and delta waves. Delta wave power values (indicated by y-axis label) refers to the averaged value of the area under the curve during continuous EEG monitoring during the LNS task. Error bars represent the standard error of the mean. *p = 0.032

Likewise, there was no difference in theta waves between concussed and non-concussed individuals (concussed, M = 64.28, SD = 19.53; non-concussed, M = 60.75 , SD = 17.55) for the forward span condition, whereas concussed individuals (M = 71.72, SD = 17.76) displayed significantly greater theta waves during the letter number reordering condition when compared to the non-concussed individuals (M = 56.91, SD = 11.59), t(14) = -2.32, p = 0.019 (see Figure 2).

Behavioral performance skills were based on the participant's accuracy on both of the LNS tasks (LNF and LNR). Although, there were no significant behavioral differences between concussed (M = 13.10, SD = 2.13; M = 10.2, SD = 3.01) or non-concussed (M = 14.06, SD = 2.27; M = 11.31, SD = 2.30) individuals for both the forward span and reordering conditions respectively, the concussed participant means for both LNF and LNR scores were lower than that of non-concussed participants (see Table 2).

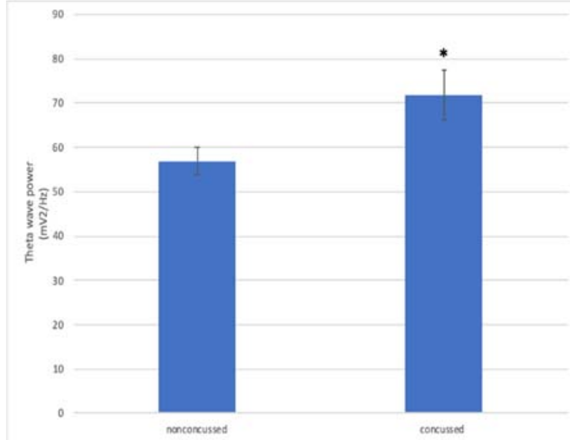

Figure 2. Increased theta waves in concussed individuals during letter number reordering task. While under continuous EEG, participants were tasked with the reordering condition of the Letter Number Sequencing task. EEG readings were analyzed by obtaining an average area of alpha, beta, theta, and delta waves. Delta wave power values (indicated by y-axis label) refers to the averaged value of the area under the curve during continuous EEG monitoring during the LNS task. Error bars represent the standard error of the mean. *p = 0.019

Table 2. Behavioral results for Letter Number Forward and Letter Number Reordering tasks.

	LNF	**LNR**
Non-Concussed	M = 14.06 SD = 2.26	M = 11.31 SD = 2.30
Concussed	M = 13.10 SD = 2.13	M = 10.20 SD = 3.01

Note. Results failed to reach significance with given sample size (p = 0.060).

Discussion

Although no significant difference was found between the behavioral scores generated from the Millisecond Letter Number Sequencing Tasks, EEG analysis showed significant increases in both delta and theta frequency bands in concussed individuals during completion of the LNR task when compared to the delta and theta frequency bands during the LNF task, indicating that mTBI disrupts the normal brain activity of injured participants when compared to non-concussed individuals.

During the reordering task, concussed individuals exhibited greater amounts of slow wave activity, indicating a possible inappropriate recruitment of resources, as was previously demonstrated in a similar study, (Chan, 2001). Current results also coincide with pre-existing literature as made evident by the frequency of elevated delta and theta power during varied executive function related tasks (McCrea et al, 2010; Scheeringa et al, 2008; Munia et al, 2017). Interestingly, other studies have found an increase in beta power in conjunction with significantly less delta and theta bands over the frontal lobe for concussed individuals, which has been hypothesized as a possible compensation mechanism for cognitive deficits that may arise post-concussion (Balkan et al, 2015; Sanchez-Carrion et al., 2008).

An increase in theta band frequency bands during time domain parameters has also been found to be associated with ADHD, hyperactivity, impulsivity, and inattentiveness (Vidaurre et al., 2009). The increased theta frequency bands observed in the concussed individuals during completion of our LNR task indicates that the injured individual may have been exerting more effort to complete the task. Therefore, it is likely that the increased theta waves could be related to possible executive function deficits resulting from mTBI; specifically, hyperactivity in the frontal lobe due to increased cognitive effort to complete working memory tasks.

An increase in delta frequency during continuous EEG has previously been associated with the indication of brain injuries, learning problems, and difficulties with cognition (Demos, 2005). Thus, our results support those findings as the increased delta waves observed in concussed individuals is likely associated with the self-reported history of concussion from participants. The results from the current study are also likely related to the long-term executive function deficits that have been previously described to be a consequence of mTBI (Howell et al, 2013).

The combination of electrophysiological results and behavioral results points towards a reorganizational hypothesis where brain networks aren't completely disrupted but are rewired. This explains why there are no behavioral changes in concussion patients; however, there is increased brain activity to overcompensate for damaged networks. This hypothesis is proposed and supported by multiple other studies (Kumar et al, 2009; Ledwidge et al, 2016).

Given that the current study was conducted under time constraints, the amount of data collection was limited to a small sample size. While trends for lower scores for both forward span and reordering span were observed in the current scope of this study, they failed to reach significance. With more time and an increased sample size, it is reasonable to posit that a general increase in statistical accuracy would occur. In addition to garnering a larger sample size, future iterations of WAIS-IV 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 platform for administration of the battery to ensure a smooth testing session.

As EEG systems are easily accessible, future directions for evaluating the long-term effects of concussions would benefit from continual pairing of EEG recording during an increased breadth of executive function demanding tasks. Neuropsychological tests included should relate to not only working memory and attention, but also cognitive flexibility, impulse control, etc. Ultimately, the determination of differences in brain activity during executive function tasks may allow for distinguishing between concussed and non-concussed individuals and symptom persistence, lending the use of EEG as a powerful clinical tool to detect frontal lobe processing differences within the two groups.

Conclusion

This research shows that although there are no differences in working memory performance, there is increased brain activation, as shown through EEG neuroimaging, in concussed participants during working memory tasks. These results point to a possible rewiring hypothesis where the neuronal networks are damaged following a concussion and reorganize to allow patients to maintain normal cognitive functioning. More collaborative research is necessary to establish a direct relationship between the delta and theta power increases associated with concussion. This study exemplifies the application of EEG as a sensitive neuroimaging technique to measure post-concussive abilities and/or deficits that may be present within patients. The Millisecond Letter Number Sequencing Task utilized in this study allows for the conclusion that concussed individuals exhibit elevated delta and theta waves as a result of mTBI and associated long-term, post-concussive deficits to working memory networks.

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