RELATIONSHIP BETWEEN OCULOMOTOR FUNCTION, NEURAL AVTIVITY, AND EVENT-RELATED DESYNCHRONIZATION IN INDIVIDUALS WITH MTBI

By

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Abstract:

Mild Traumatic brain injuries (mTBI) can lead to vision and visual processing deficits, including decreased visual acuity, visual field impairment, eye movement dysfunction including vergence, saccadic, smooth pursuit movements, and an increase in mental workload during visual tasks. Also, evidence shows a relationship between visual tracking performance and brain activity function. Recent brain activity research (as measured via EEG) have indicated differences between mTBI patients and healthy controls. Specifically, mTBI patients demonstrated decreased alpha activity with a corresponding increase in theta activity and an overall increase in cognitive effort during visual and motor tasks. The purpose of this project was to examine the relationship between brain activity and visual motor deficit in patients with mTBI compared to healthy controls. Our hypothesis was that individuals who have experienced mTBIs within the past year would show changes in alpha desynchronization and perform poorer in visual tracking tasks than healthy participants. We also hypothesized a relationship between EEG desynchronization and visual tracking performance. To test these hypotheses, 26 participants (17 concussed and 9 non-concussed) wore a 32-channel dry EEG cap while completing a series of RightEye visual tracking tasks. Eye movements were recorded using an infrared remote eye tracker while theta and alpha power within spectral analysis were used to indicate changes in brain function. Our results show increased cognitive workload during smooth pursuit and discriminant reaction time tasks for those in the mTBI group. Participants in our study that experienced mTBIs within the past year demonstrated changes in alpha desynchronization and performed poorer in visual tracking tasks than healthy participants. Our results support the idea that mTBIs cause increased cognitive workload in regions of the brain that impact visual acuity.

Introduction

In recent years, discussions concerning minor traumatic brain injuries (mTBIs) and their associated effects on visual processing have been a topic of multiple studies. Prior research has established that mTBIs can have detrimental short-term effects to cognitive processing and the coordination of eye movements (Cifu et al., 2015). Various eye movements such as saccadic, smooth pursuit, and fixation stability are controlled by areas of the brain that may be affected when an individual suffers an mTBI. When a visual signal is received by the retina it is distributed through a complex neural network. After passing through the retina the visual signal arrives at the superior colliculus and the processed by the joint effort of the lateral geniculate nucleus, pulvina and mediodorsal thalamus. This complex is where top-down processing of the visual signal occurs. The pre-frontal cortex, areas of the parietal lobe, temporal lobe, and brainstem work in coordination with each other to properly interpret the visual signal. (Stuart et al., 2020, p. 2). Given that the areas of the brain that are responsible for vision and visual processing are dynamic and interconnected, any disruption such as that caused by an mTBI may affect visual acuity. Minor traumatic brain injuries are observed in a clinical setting by physicians that may choose to use EEG and eye-tracking data to diagnose and determine severity. For populations that have experienced brain injury, eye movements have become a topic of study as they seem to be consistently affected by mTBIs. Many studies such as the one conducted by Cifu et al., have focused primarily on saccadic, smooth pursuit, and fixations as eye movements that are discernably different between those with and without mTBI (Cifu et al., 2015).

Eye tracking has been measured via the use of many tools in the past such as “large-scale photographic technology” and “invasive scleral search coils.” However, most researchers are currently using modern infrared camera systems to track eye movements. Some studies have chosen to observe eye movements while participants are static, while others have made adaptations to observe eye-tracking in a mobile environment (Stuart et al., 2020, p. 2). All studies, referenced by Stuart et al. (2020), regardless of being mobile or static focused on the same saccadic, smooth pursuit, and fixation stability movements as indicators to be considered when researching effects of mTBIs.

Danna-Dos-Santos et al., (2018) provides evidence that supports the idea of long-term impacts on oculomotor tracking among individuals that have experienced an mTBI. Their study examined a sample of 36 individuals that had experienced mTBI. Their experimental group consisted of a cohort with an average 2.47 traumatic episodes per participant and an average of 43.11 months between the last traumatic episode and the time of data collection. The study found it significant that participants with mTBI experienced saccadic intrusions during the smooth pursuit test, and these intrusions lasted several months post mTBI. Saccadic intrusions are irregular rapid eye movements that are separated by a brief pause in which the eyes are still. In addition to the increased saccadic intrusions during smooth pursuit tests, Danna-Dos-Santos et al. (2018), also found individuals with mTBI had increased visual reaction time, and poorer accuracy during tests measuring saccadic movements (Danna-Dos-Santos et al., 2018). Given their sample consisted of individuals that were on average 43.11 months post mTBI, their study provides support for the idea that mTBIs may have longer lasting impacts than previously expected on the complex network of neural pathways that control visual processing.

Previous research has supported long lasting visual processing issues are due to lack of oculomotor control in mTBI patients (Danna-Dos-Santos et al., 2018). These findings necessitate a need for investigative researchers and physicians to have access to diagnostic tools that enable accurate testing of oculomotor function in a variety of settings. Currently physicians have a standard for judging their patient's eye tracking capabilities which includes asking them to follow their finger and observing how their patient responds with the "naked eye" (Murry et al., 2019). This technique is useful but lacks the ability to accurately gauge the severity of the patient's reduced oculomotor control. An emerging technology developed by RightEye has demonstrated reliability as an effective tool for measuring oculomotor behavior metrics. Their system uses an infrared eye tracker to monitor oculomotor movements during visual tracking tasks. Murry and others completed an in-depth analysis of the RightEye tracking system across a cohort of 2993 healthy participants stratified by age group. They conducted visual tracking tests including circular smooth pursuit, vertical smooth pursuit, horizontal smooth pursuit, horizontal saccade, and vertical saccade. They determined that a significant portion of their variables (85%) were rated at acceptable or higher reliability, which demonstrates a high level of reliability for the RightEye system as a diagnostic tool. Murry and others mentioned, their only unreliable metric was synchronization within the circular smooth pursuit, and vertical pursuit tests. Though they recognized no previous methods had been established to accurately gauge synchronization for those two oculomotor movements. (Murry et al., 2019). Their analyses support that RightEye has developed a tool suitable for further research regarding visual tracking. Though eye-tracking has provided significant data, including comparative EEG analysis will allow researchers to understand how mTBIs affect visual processing at the neurological level.

In addition to eye-tracking as a measure of mTBI affects; researchers have explored studying EEG analysis. Researchers have analyzed their EEG data to extrapolate useful measures of relative brain activity. The methods of analyzing EEG data have varied between studies dependent on their focus. Studies such as the one conducted by McNerney, et al., (2019) that are interested in assessing new techniques for diagnosis of mTBIs may tend to focus on analyzing power spectral densities (PSD). PSDs are used to demonstrate variances in overall brain activity at any given time. An analysis of PSD provides the researcher information specific to the distribution of power in an EEG signal relative to the frequency domain. Researchers interested in understanding the variances in electrical activity at the moment directly after an event or stimuli may consider analyzing EEG data to extrapolate instances of event related synchronization (ERS) and event related desynchronization (ERD). According to Arakaki et al. (2018), oscillatory electrical signals in the alpha band which occur between 8–12 Hz are the most prevalent oscillation in human brains and is the only activity that responds to a stimulus with both a decrease and an increase in power. This means that the alpha frequency ERD is followed by a period of ERS (Arakaki et al., 2018). Arakaki mentions that alpha ERD is related to fronto-parietal network activity during working memory tasks. This is a notable association given the relation between the frontal and the parietal lobes during visual tracking tasks. The study conducted by Arakaki et al., specified 3 data collection sessions for all participants. Data was collected within five days, two weeks post mTBI, and one month after mTBI. As a result, they determined induced and evoked alpha ERD and ERS were abnormal among their mTBI group (Arakaki et al., 2018). The results of their study suggest that fronto-parietal electrical networks are significantly impacted in the month following an mTBI.

Our study hopes to provide evidence relevant to discovering if neural pathways may remain damaged up to and including one year post injury. The purpose of this project is to test and understand the relationship between brain activity and visual motor deficit in patients with mTBI compared to healthy controls. Our hypothesis is that individuals who have experienced mTBIs within the past year will show changes in alpha desynchronization and perform poorer in visual tracking tasks than healthy participants. We also hypothesize a relationship between EEG desynchronization and visual tracking performance. We hope this will help guide future research and ultimately contribute to our understanding of the associations between visual motor deficits and mTBIs.

Literature Review:

In recent years the public has become increasingly interested in if concussions may cause deficits that last longer than they are currently known to. One interesting correlation that raises interest about the longevity of mTBI effects is that the medical community has observed an increased chance of reinjury suffering an mTBI (Zuckerbraun et al., 2014). This is an interesting observation in that it adds to the discussion regarding the duration of mTBI effects and why further research is necessary for the well-being of the public. The correlation between experiencing an mTBI and the chance of reinjury suggests that there is some connection between the brain injury and routine physical movement. Several studies have discussed significant evidence in support of long-lasting effects of mTBIs and their association with oculomotor control. E.g., the Danna-Dos-Santos (2018) study found that the absence of visual information for brief periods of time could cause changes in neural mechanisms possibly associated to the origination of multi-muscle synergies among muscles associated with posture control in healthy adults. (Danna-Dos-Santos et al., 2018). This study and other related studies have shown that visual perception can be significantly impacted after an mTBI occurs. This, in conjunction with evidence that people who have mTBIs experience different eye movement behavior when navigating complicated environments helps provide an idea as to the connection between mTBIs, visual tracking, and diminished control over decision making regarding body movement (B. et al., 2012).

There has been research focusing on the differences in visual movements for those who have suffered an mTBI. An emerging technique is using infrared eye-tracking technology to analyze various eye movements. RightEye's infrared eye-tracking system has been tested to discern its accuracy and capabilities for various eye movements. The effectiveness of the system has shown to be promising. Murray et al. (2017) tested the RightEye infrared system to determine its ability to monitor interpupillary distance and pupil diameter using central point stimuli and an infrared eye-tracker. Out of a sample of 416 people, 50 participants composed the group who's purpose was testing the accuracy and reliability of the RightEye system within the study. They compared RightEye system to other known eye-tracking tools such as the PL850 and Essilor Digital CRP. Their results were very strong ($P < .001$) and supported the idea that the RightEye system is effective for monitoring variances in pupil status during experimental eye tracking tasks. Their conclusion mentioned the reason that RightEye system may be helpful for a multitude of eye-tracking experiments is that it allows for a central point of fixation which limits variability when measuring pupil diameter under experimental conditions (Murray et al., 2017). After establishing that Righteye's system is accurate when measuring variances in pupil status during experimental conditions, it is necessary to ensure that the system is applicable for monitoring various eye movements prior to employing it in an mTBI study.

RightEye's infrared eye-tracking system has shown to be effective and efficient at measuring simple reaction time (SRT), choice reaction time (CRT), and discriminate reaction time (DRT). A study by Lange, et al. (2018), found that the RightEye system and their associated visual tracking tests are reliable and accurate at discerning variances in reaction times when comparing a healthy population to a population with mTBI. Below are their results indicating statistical significance and justifying RightEye as an accurate system for measuring variances in reaction time.

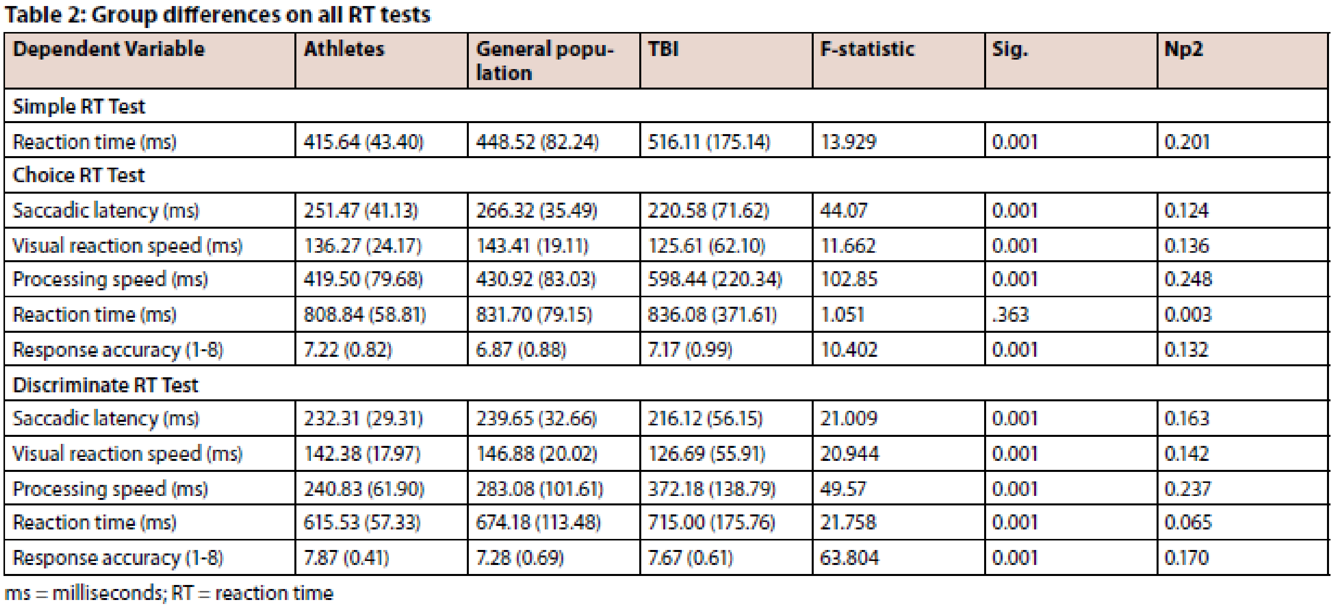

Table 2: Group differences on all RT tests

Dependent Variable	Athletes	General population	TBI	F-statistic	Sig.	Np2
Simple RT Test						
Reaction time (ms)	415.64 (43.40)	448.52 (82.24)	516.11 (175.14)	13.929	0.001	0.201
Choice RT Test						
Saccadic latency (ms)	251.47 (41.13)	266.32 (35.49)	220.58 (71.62)	44.07	0.001	0.124
Visual reaction speed (ms)	136.27 (24.17)	143.41 (19.11)	125.61 (62.10)	11.662	0.001	0.136
Processing speed (ms)	419.50 (79.68)	430.92 (83.03)	598.44 (220.34)	102.85	0.001	0.248
Reaction time (ms)	808.84 (58.81)	831.70 (79.15)	836.08 (371.61)	1.051	.363	0.003
Response accuracy (1-8)	7.22 (0.82)	6.87 (0.88)	7.17 (0.99)	10.402	0.001	0.132
Discriminate RT Test						
Saccadic latency (ms)	232.31 (29.31)	239.65 (32.66)	216.12 (56.15)	21.009	0.001	0.163
Visual reaction speed (ms)	142.38 (17.97)	146.88 (20.02)	126.69 (55.91)	20.944	0.001	0.142
Processing speed (ms)	240.83 (61.90)	283.08 (101.61)	372.18 (138.79)	49.57	0.001	0.237
Reaction time (ms)	615.53 (57.33)	674.18 (113.48)	715.00 (175.76)	21.758	0.001	0.065
Response accuracy (1-8)	7.87 (0.41)	7.28 (0.69)	7.67 (0.61)	63.804	0.001	0.170

ms = milliseconds; RT = reaction time

(Lange, et al., 2018)

Based on the analysis of the technology, Utilizing RightEye's infrared eye-tracking has been shown to be appropriate for analyzing differences in eye-tracking between healthy and mTBI populations.

Methods:

Participants:

Participants were recruited in multiple ways including mass email, flyers, and word of mouth. Beginning in March of 2021, $25 gift cards were offered as reimbursement.

Our study included 9 concussed participants as our experimental group and 17 healthy participants were our control. Out of the 26 total participants, 74% of participants were female, 26% were male. Within our screening survey, 57% of our mTBI participants were reported having been concussed due to athletics. The average age of our participants was 21 years old. Our participants reported an average time between mTBI and data collection of 6.85 months. Slightly less than half (43%) of our concussed participants reported being hospitalized, having become unconscious, and/or lost memory due to a head injury/concussion and 71% of our participants reported having frequent headaches as a result of their mTBI.

Equipment:

All data was collected using the same equipment. For the eye-tracking portion of our data collection, the RightEye infrared eye-tracking system was used. Participants sat approximately 60 cm from a computer monitor equipped with the infrared system and the RightEye Dynamic Vision visual tracking-tests. To monitor brain function during tasks, participants wore a 32-channel g.Nautilus dry and Bluetooth equipped EEG cap manufactured by G.Tec Medical Engineering. Using this cap allowed for shorter data collection times and a relatively mess-free environment compared to other EEG caps. During EEG preparation, lemon prep, alcohol prep pads, and a tape measure were used. G.Tec's EEG software was used to at the time of collection to record EEG data. Data analysis required the use of MATLAB's EEGLAB function for preprocessing and postprocessing. SPSS software was also utilized for a comparative analysis of both eye-tracking and EEG data between concussed and healthy groups.

Procedure:

Participants completed the mTBI survey in which they specified if they had a diagnosed concussion in the past 1 year. If so, they were asked the approximate date their mTBI occurred, and how they were injured. After completing the survey participants sat in a chair and were prepped to wear the wireless, Bluetooth EEG cap. The specific EEG cap that was used is the 32-channel g.Nautilus model manufactured by G.Tec Medical Engineering. For placement to meet the 10/20 system, participants are measured from their nasion to their inion, and a small mark was placed (1/10th of the distance using the nasion as the reference) on the participant's forehead with a washable marker. The front edge of the cap was aligned with the mark, ensuring that the cap was placed appropriately. The next step was to prep the mastoid regions behind each ear, where two reference electrodes were placed. A small gauze pad with a mild abrasive skin prepping lotion (Lemon Prep) was used to abrade the area behind each ear. This served to clear the area of dead skin cell and allow the reference electrodes to make good contact with the skin. Alcohol prep pads were then used to clean the area. After prepping the mastoid region was complete, one reference electrode was placed behind each ear to serve as a reference for the EEG signal. The chin strap was attached and tightened to the appropriate level, considering participant comfort. One researcher then ensured that the EEG data collection software, also manufactured by G.Tec Medical Engineering, is set to the appropriate specifications. For our study, a custom setup was established and used for every participant. This custom set up ensured that the EEGLAB software recognized our cap as a 32-channel EEG and not the standard 64-channel cap. Once the EEG preparation was complete, attention was directed to setting up the RightEye tracking software.

For the visual tracking portion of the experiment we utilized RightEye's Dynamic Vision Module. The participant sat approximately 60 cm from a computer monitor equipped with the infrared tracking system. Once the participant was appropriately positioned, the RightEye we calibrated the RightEye system via a 9-point calibration. Participants then began a series of visual tracking tasks in this order: circular smooth pursuit (CSP), horizontal smooth pursuit (HSP), vertical smooth pursuit (VSP), horizontal saccade (HS), vertical saccade (VS), fixation stability (FS), choice reaction time (CRT), and discriminant reaction time (DRT). At the beginning of each task, a researcher began recording EEG data on the G.Tec software. A marker was placed at the beginning and conclusion of each visual task to indicate the period associated with the eye-tracking task. At the conclusion of the visual tracking tasks, the EEG cap was removed from the participants, including the two electrodes from each mastoid region. The cap was cleaned using a disinfectant spray.

Data processing:

The first step in the analysis of our EEG data was to run data through MATLAB's EEGLAB tool. A series of 3 separate codes were developed by faculty at East Carolina University that cleaned the EEG files of any extraneous noise and ensured the files were configured for the 32 channel EEG cap. SPSS software was used to apply comparative statistics to both EEG and eye-tracking data to determine statistical significance. These statistics were applied to all eye-tracking data and EEG data from the CSP, HSP, VSP, and DRT tasks.

Data analysis:

Eye-tracking data was analyzed through the SPSS general linear model to reveal any statistically significant trends between concussed and healthy participants. Analysis of eye-tracking data revealed differences between concussed and healthy participants, though not statistically significant. Regarding variances in smooth pursuit accuracy between groups, F (1, 797.376) = 2.324; p = 0.140. Differences in reaction time during DRT tasks were indicated by F (1, 8944.501) = 0.269; p = 0.609. We believe the variances were likely impacted by our small sample size. We did note disparities during all three smooth pursuit tasks and during discriminant reaction time tasks. The observed differences led us to focus analysis of EEG data on those four tasks. The EEG data was analyzed through an excel spread sheet where the equation, $dB\ power = 10\ log10\ \frac{power}{baseline}$ allowed us to extrapolate variances in ERD/ERS and compare between concussed and healthy participants. The resulting Alpha and Theta values for CSP, HSP, VSP, and DRT tests were entered into SPSS to discern whether any statistically significant variances in alpha or theta ERD/ERS were present in our data. EEG analysis revealed consistent, statistically significant discrepancies between groups dependent on tasks and region of the brain.

Results:

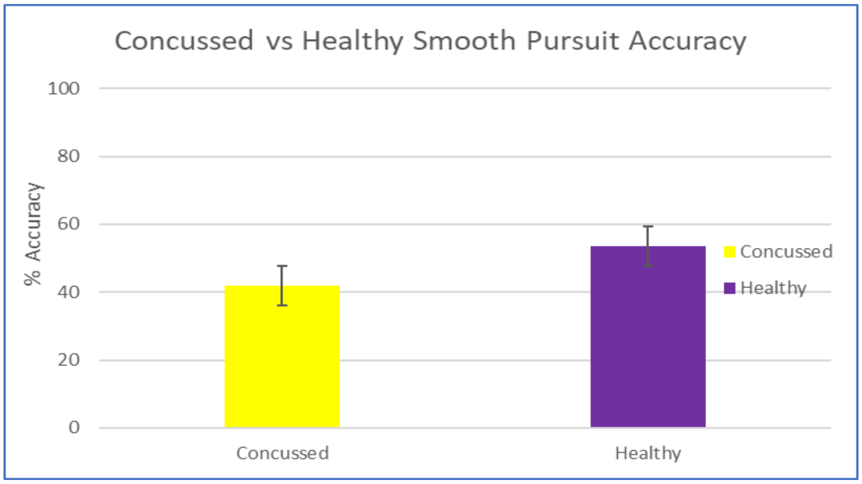

Figure 1. Demonstrates the observed differences in eye-tracking accuracy between concussed and healthy participants during smooth pursuit tasks.

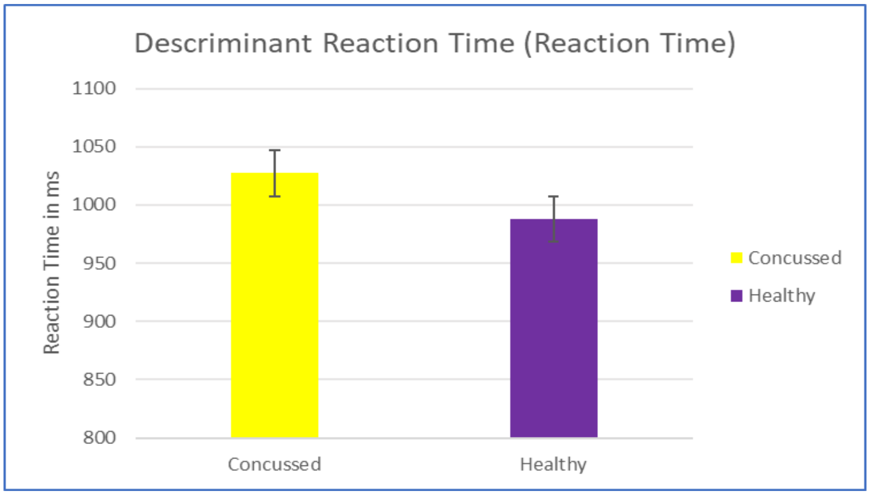

Figure 2. Demonstrates the observed differences in reaction time between concussed and healthy participants during discriminant reaction time tasks.

Eye-Tracking:

Trends, though statisitistically insignificant were observed within our eye-tracking data. Participants with mTBI performed with poorer accuarcy during smooth pursuit tests as indicated by Figure 1. Smooth pursuit accuracy was not statistically different between groups (P = 0.140). Participants with mTBI also had slower reaction times during the DRT task when compared to healthy participants which is shown in Figure 2. Reaction time for the DRT task was not statistically different between groups either (P = 0.609). We focused on these trends as we processed our brain activity data.

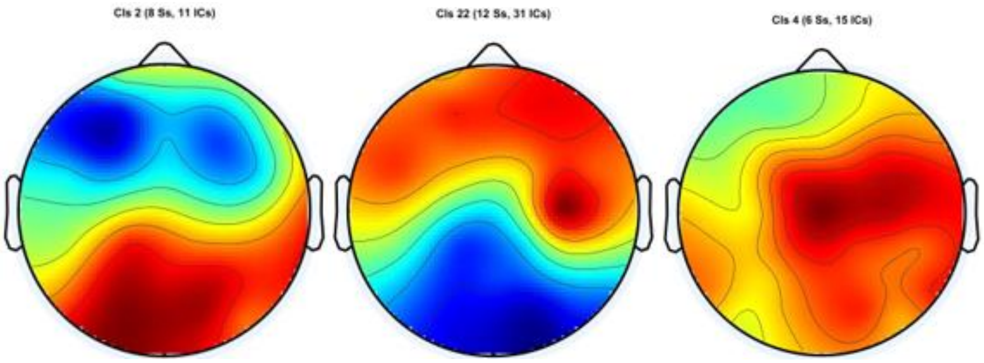

Figure 3. **Figure 4.** **Figure 5.**

Figures 3, 4, and 5 show increased neural activity during circular smooth pursuit tasks averaged across all participants and served as a reference for frequency level analysis. Figure 4 demonstrates the increased neural activity in the frontal-parietal region during the circular smooth pursuit task.

		Left_Frontal	Right_Frontal	Left_Central	Right_Central	Left_Frontal-Central	Right_Frontal-Central	Left_Parietal	Right_Partietal	Left_Parietal-Occipital	Right_Parietal-Occipital
Alpha_CSP	Concussion	0.62 (1.18)	0.56 (0.91)	1.04 (1.59)	0.93 (1.64)	0.58 (1.00)	0.43 (0.66)	0.42 (0.70)	0.42 (0.67)	0.39 (0.68)	0.35 (0.76)
	Healthy	1.69 (1.53)	1.86 (1.62)	2.4 (2.27)	1.44 (1.07)	2.38 (3.55)	2.62 (3.03)	1.56 (1.23)	2.28 (2.59)	1.86 (3.03)	1.40 (1.17)
Alpha_DRT	Concussion	0.47 (1.28)	0.41 (0.98)	0.42 (0.97)	0.51 (1.40)	0.39 (0.90)	0.27 (0.53)	0.24 (0.52)	0.24 (0.54)	0.22 (0.44)	0.29 (0.83)
	Healthy	2.31 (5.08)	1.12 (0.58)	3.51 (6.89)	1.35 (1.01)	2.92 (5.80)	1.99 (2.09)	2.08 (3.96)	4.99 (12.36)	1.14 (0.74)	2.88 (5.62)
Alpha_VSP	Concussion	0.49 (0.83)	0.7 (1.23)	0.42 (0.63)	0.80 (1.11)	0.82 (1.38)	0.48 (0.77)	0.30 (0.43)	0.40 (0.63)	0.40 (0.61)	0.56 (0.97)
	Healthy	1.34 (1.21)	1.29 (0.98)	1.29 (0.86)	1.32 (1.34)	1.26 (1.45)	1.64 (2.27)	1.31 (1.16)	1.07 (0.78)	1.56 (1.61)	1.20 (1.13)
Alpha_HSP	Concussion	0.48 (0.89)	0.42 (0.72)	0.70 (1.05)	0.70 (1.29)	0.44 (0.70)	0.33 (0.55)	0.36 (0.60)	0.33 (0.57)	0.52 (0.91)	0.40 (0.74)
	Healthy	1.04 (0.67)	1.28 (0.94)	1.33 (1.44)	1.02 (1.00)	1.76 (3.71)	1.61 (2.09)	0.91 (0.57)	1.45 (1.59)	0.98 (0.52)	1.13 (1.12)

Table 1. Variances in ERS/ERD within alpha frequencies (8-12 Hz) were compared between concussed and healthy participants for smooth pursuit and discriminant reaction time tasks. Highlighted values indicate significant differences ($P \leq 0.05$) between concussed and healthy individuals.

		Left_Frontal	Right_Frontal	Left_Central	Right_Central	Left_Frontal-Central	Right_Frontal-Central	Left_Parietal	Right_Partietal	Left_Parietal-Occipital	Right_Parietal-Occipital
Theta_CSP	Concussion	1.00 (1.96)	0.49 (0.76)	0.84 (1.28)	0.71 (1.08)	0.38 (0.56)	0.37 (0.52)	0.64 (1.04)	0.49 (0.73)	0.62 (1.16)	0.21 (0.40)
	Healthy	1.32 (0.86)	1.38 (1.24)	2.22 (2.71)	1.19 (0.85)	1.65 (1.55)	1.86 (2.01)	1.43 (0.85)	1.50 (1.40)	1.20 (0.96)	0.64 (0.49)
Theta_VSP	Concussion	0.96 (1.75)	0.39 (0.61)	0.71 (1.18)	0.72 (1.2)	0.33 (0.47)	0.33 (0.51)	0.50 (0.73)	0.44 (0.65)	0.75 (1.21)	0.38 (0.55)
	Healthy	1.41 (0.80)	1.46 (1.47)	1.46 (1.83)	1.01 (0.72)	1.47 (1.67)	1.29 (1.51)	1.15 (0.79)	1.24 (1.12)	1.17 (0.93)	0.84 (1.15)
Theta_HSP	Concussion	0.54 (1.03)	0.27 (0.47)	0.45 (0.69)	0.51 (0.84)	0.25 (0.38)	0.25 (0.38)	0.37 (0.61)	0.32 (0.55)	0.67 (1.30)	0.28 (0.52)
	Healthy	1.23 (0.87)	1.7 (2.01)	1.55 (2.09)	0.96 (0.95)	1.64 (2.70)	1.30 (1.48)	1.12 (0.79)	1.18 (1.12)	2.17 (3.23)	0.55 (0.52)
Theta_DRT	Concussion	0.80 (1.68)	0.31 (0.53)	0.37 (0.57)	0.52 (0.93)	0.27 (0.41)	0.29 (0.51)	0.45 (0.74)	0.45 (0.71)	0.63 (1.05)	0.24 (0.54)
	Healthy	1.58 (1.57)	1.7 (1.76)	5.36 (16.01)	1.12 (0.90)	2.63 (5.48)	1.30 (1.27)	1.43 (1.70)	1.80 (2.01)	2.68 (5.15)	2.09 (3.69)

Table 2. Variances in ERS/ERD within theta frequencies (4-8 Hz) were compared between concussed and healthy participants for smooth pursuit and discriminant reaction time tasks. Highlighted values indicate significant differences ($P \leq 0.05$) between concussed and healthy individuals.

ERD/ERS:

Variances in event-related desynchronization were present and statistically significant in our data. The results in Table 1 and Table 2 showed statistically significant variances between concussed and healthy participants with regards to ERD/ERS in both alpha and theta bands in various regions of the brain. The right side of the brain, specifically the right frontal and right parietal lobes showed more ERD/ERS than the left side of the brain across our sample population.

Healthy participants
Alpha frequency

mTBI participants
Alpha frequency

Healthy participants
Theta frequency

mTBI participants
Theta frequency

Figure 6

Circular Smooth Pursuit Neural Activity

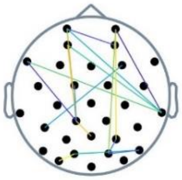

Figure 6.A

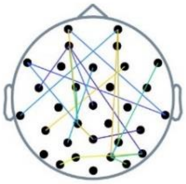

Figure 6.B

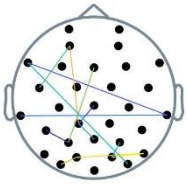

Figure 6.C

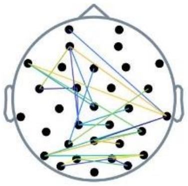

Figure 6.D

Figure 7

Horizontal Smooth Pursuit Neural Activity

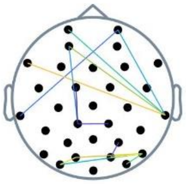

Figure 7.A

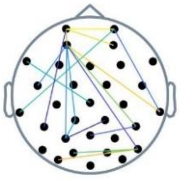

Figure 7.B

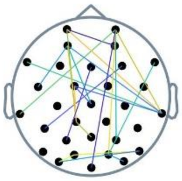

Figure 7.C

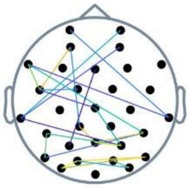

Figure 7.D

Figure 8

Vertical Smooth Pursuit Neural Activity

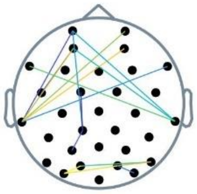

Figure 8.A

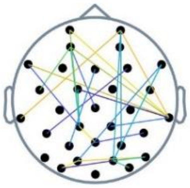

Figure 8.B

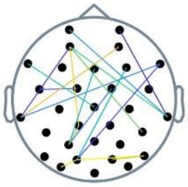

Figure 8.C

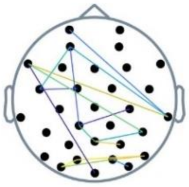

Figure 8.D

Figure 9

Discriminant Reaction Time Neural Activity

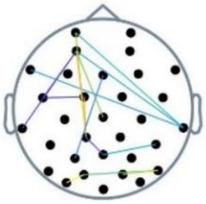

Figure 9.A

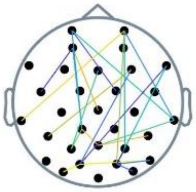

Figure 9.B

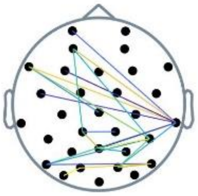

Figure 9.C

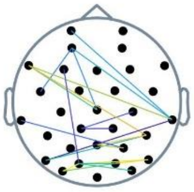

Figure 9.C

Cognitive Workload

All four tasks that were analyzed: CSP, HSP, VSP, and DRT showed observable increased neural activity and inter-regional communication within the alpha band for concussed participants compared to healthy participants. However, CSP was the only task in which mTBI participants showed an observable increase in cognitive workload within the theta band.

Discussion:

Mild traumatic brain injuries affect various eye movements such as smooth pursuit, saccadic, and fixation (Stuart et al., 2020). Our results support the idea that people who have experienced an mTBI within the past 1 year have deficits in eye-tracking. Participants in our concussed group performed poor in smooth pursuit accuracy when compared to those in our healthy group (See: Figure 1). After analyses, our eye-tracking data did not support our hypothesis that mTBI participants would perform significantly worse in visual tracking tasks than healthy participants. However, we noted impairment in smooth pursuit accuracy was a consistent trend for those in our concussed group. The disparity in smooth pursuit accuracy is supported in the literature as the Danna-Dos-Santos et al. (2018) study resulted in mTBI participants performing significantly worse ($P = 0.0289$) in smooth pursuit accuracy. Participants with mTBI showed deficits in reaction time during the discriminate reaction time task (See: Figure 2). The trend of concussed participants performing poorer during the DRT task was consistent, but not statistically significant. The Danna-Dos-Santos et al. (2018) study supports the idea that people with mTBI often have slower reaction times. Though the study measured simple reaction time, they found that mTBI participants had slower reaction times to visual signals ($P<0.001$) (Danna-Dos-Santos et al., 2018). The trends of poorer visual tracking for the 3 smooth pursuit tasks, and discriminant reaction time task served as a reference for our selection of tasks when analyzing EEG data. Participants with mTBI showed deficits in both eye-tracking and EEG data during smooth pursuit and discriminate reaction time tasks. The increased ERD (See: Table1 and Table 2) among mTBI participants was consistent during smooth pursuit and discriminate reaction time tasks which suggests a possible relationship between oculomotor dysfunction and increased neural activity associated with mTBI.

For frequency level analysis, head maps highlighting neural activity were generated so that we could observe variations in cognitive workload during smooth pursuit tasks (See: Figures 3, 4, and 5). Neural activity was increased in the frontal-parietal region during the circular smooth pursuit task for mTBI participants (See: Figure 4). Given the correlation between increased neural activity and trends from the eye tracking data, we made the decision to analyze CSP, HSP, VSP, and DRT tasks for event-related desynchronization in the alpha and theta bands of our EEG data.

Event-related desynchronization within the alpha band is related to memory storage and event-related synchronization is related to memory retention within the alpha frequency range (Arakaki et al., 2018). Our results showed statistically significant variances between concussed and healthy participants with regards to ERD/ERS in both alpha and theta bands in various regions of the brain (See: Table 1 and Table 2). The right side of the brain showed more statistically significant variances in our data and it is predominantly responsible for visual memories. The frontal and parietal lobes were the regions of the brain that showed the most variance in ERD/ERS. The frontal lobe is responsible for cognitive function and control of voluntary movement while the parietal lobe is responsible for integrating sensory information, specifically vision, to form what we understand as cognition. Similarly, Arakaki et al. (2018) found that frontal induced alpha ERD was greater in mTBI participants. Their results showed statistically significant differences in alpha ERD between mTBI and healthy participants 2 weeks after injury (P = 0.13) and one month after injury (P =0.04) (Arakaki et al., 2018).

People with mTBI often show negative changes in executive function and increased cognitive workload compared to those who have not experienced a concussion (Poltavski et al., 2019). Also, Arakaki et al. (2018) mentions there is a relationship between attention/memory tasks and alpha oscillation. To gain a better understanding of the increased cognitive workload that our concussed participants demonstrated, we produced head maps for each test condition and separated based on frequency (See: Figures 6, 7, 8, and 9). Only the CSP task resulted in a major difference between groups in cognitive workload for both alpha and theta frequencies (See: Figure 6). All four tasks that were analyzed: CSP, HSP, VSP, and DRT showed observable increased neural activity within the alpha band for concussed participants compared to healthy participants. The connection between increased mental workload and mTBI is supported by the Arakaki et al. (2018) study which found that after their participants third visit (one month post-mTBI) participants with mTBI showed the use of increased effort as a compensation for a deficit in information retention. Longitudinal studies focusing on ERD and cognitive workload up to one year post-mTBI would be helpful in understanding cognitive workload in people with mTBI.

Our study supports the hypothesis that individuals who have experienced mTBIs within the past year would show changes in alpha desynchronization and perform poorer in visual tracking tasks than healthy participants. There were statistically significant changes in alpha and theta ERS/ERD between concussed and healthy participants. Future research should include a larger sample size to explore if there is statistically significant correlation between eye-tracking deficits and increased cognitive effort during visual tracking tasks. We conclude that mTBIs cause increased cognitive workload in regions of the brain that impact visual acuity.

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