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Joseph Ferraracci
University of South Carolina

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QEEG Correlates of Cognitive Processing Speed in Children with Traumatic Brain Injuries

by

Joseph Ferraracci

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Accepted by:

Scott Decker, Director of Thesis

Jeff Schatz, Reader

Cheryl L. Addy, Vice Provost and Dean of the Graduate School

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ABSTRACT

Electroencephalography (EEG) and neuropsychological test measures have been previously used to understand the underlying brain changes in individuals with a traumatic brain injury (TBI). However, literature discussing the relationship between EEG and neuropsychological test performance is scarce and, further, has not been investigated explicitly in children. The purpose of this study is to investigate the cognitive and academic deficits in children with traumatic brain injury and, additionally, this study aims to understand the underlying relationship between EEG and neuropsychological test performance among this sample. Analyses included twenty-one participants between the ages of 8 and 19 years of age (male, n=14; female, n=7). Mean subtest and composite scores were compared to the WJ-IV normative sample mean. Regression analyses were used to determine whether EEG alpha and beta coherence values were related to the processing speed composite score (Gs) from the Woodcock-Johnson IV Tests of Cognitive Abilities (WJ-IV Cog). The current study found that children with TBI exhibit general deficits across all subtests below what would be expected of the general population. Further, several coherence measures in the alpha and beta bands could significantly predict processing speed scores. Findings from this study provide evidence of a relationship between EEG and the Gs composite score on the WJ-IV Cog.

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CHAPTER 1

INTRODUCTION

1.1 TBI Information

A traumatic brain injury (TBI) is an alteration in brain function caused by an external force (Menon, Schwab, Wright, and Maas, 2010). General, defining symptoms of TBI include: loss of consciousness; memory loss for events before or after the injury; neurological deficits (such as weakness, vision changes, aphasia, etc.); or any change in mental state (such as confusion or slowed thinking). A recent report from the National Center for Injury Prevention and Control reports approximately 1.7 million people each year sustain a TBI. Of these, about 50,000 die, 275,000 are hospitalized, and 1.365 million are given care and released from the emergency department. Further, about 511,000 TBI's happen to children between the ages of 0 and 14, accounting for almost one-third TBI's, and children between the ages of 0-4 and 15-19 years old are in the highest risk category for TBI (Langlois et al., 2006). According to the report, TBI's occur primarily due to falls although motor-vehicle accidents are the primary cause of TBI-related deaths (Faul, Xu, Wald, & Coronado, 2010).

The overall estimate of 1.7 million is likely to be an underestimate of the actual number of TBIs for a variety of reasons. First, individuals may seek other forms of medical treatment outside of emergency department rooms that are not tracked as stringently such as a primary care physician. Next, individuals may be misdiagnosed by medical professionals regardless of their setting. Additionally, data reported by US databases often do not include individuals treated for TBI in military facilities (Langlois et al., 2006). Finally, individuals may not seek treatment at all (Faul et al., 2010), as the general public has limited awareness and knowledge of what a TBI is. Indeed, the report by Faul et al. (2010) only included incidents of TBI that resulted in emergency department visits. This limited understanding has rendered TBI as a “silent epidemic” (Faul et al., 2010; Roozenbeek, Maas, & Menon, 2013).

Given the prevalence of TBI in young children and adolescents, as well as the subsequent complications and limited understanding, it is important to understand how TBI’s affect youth in the academic setting. Schools and other educational institutes are legally mandated to provide support to children diagnosed with a TBI. As defined in Section 300.8(c)(12) of the Individuals with Disabilities Education Act (IDEA), a traumatic brain injury is:

> “…an acquired injury to the brain caused by an external physical force, resulting in total or partial functional disability or psychosocial impairment, or both, that adversely affects a child's educational performance. Traumatic brain injury applies to open or closed head injuries resulting in impairments in one or more areas, such as cognition; language; memory; attention; reasoning; abstract thinking; judgment; problem-solving; sensory, perceptual, and motor abilities; psychosocial behavior; physical functions; information processing; and speech. Traumatic brain injury does not apply to brain injuries that are congenital or degenerative, or to brain injuries induced by birth trauma.” [34 *Code of Federal Regulations* §300.8(c)(12)]

Therefore, any child with a TBI that results in a disability, whether short-term or long-term, must receive accommodations. Such accommodations will depend on the symptoms they present but can include more time on tests, scheduled breaks, alternate work, and removal from physical activities. Consequently, it is important that schools assess individuals to determine what areas have and have not been impacted by a TBI in order to provide accommodations best matched to their symptoms. Thus, assessments must be sensitive to the various deficits that may be present in a child with a TBI.

Although children are at the highest risk for TBI, disability services for children with TBI are unreliable, if not completely absent (Arroyos-Jurado, Paulsen, Merrell, Lindgren, & Max, 2000). Unfortunately, school personnel are not adequately trained to assess children with TBI (Glang, Tyler, Pearson, Todis, & Morvant, 2004) despite the legal implications. Thus, many children with TBI remain unidentified in educational settings. For example, Glang et al. (2004) conservatively estimate that around 390,000 children between kindergarten and twelfth grade would sustain a TBI that resulted in disability. They further estimate that if only a third of those children required special education, the number of children who should receive special education under the TBI category should equal 130,000 students; however, according to the Twenty-Fourth Annual Report to Congress on the Implementation of the Individuals with Disabilities Education Act (2002), only 14,844 children between the ages of 6 and 21 were served under the TBI category. Even with Glang et al.'s (2004) conservative estimates, the difference between the number of children receiving services and the number of children who are expected to need services is staggering. Given the previously mentioned importance of assessing children accurately, neuropsychological assessments used in schools must be able to correctly locate children suffering from cognitive deficits related to TBI. Moreover, the assessments must be able to identify specific weaknesses in order to provide the best suited accommodations for the individual.

1.2 TBI Symptoms

There are numerous complications that can occur because of a TBI including physical, emotional, and cognitive changes (Belanger, Curtiss, Demery, Lebowitz, & Vanderploeg, 2005) as well as behavioral changes (Langlois, Rutland-Brown, & Wald, 2006). Physical changes may include headaches, blurry vision, fatigue, and nausea. Emotionally, individuals may become more irritable or anger easily (“Head, 1993;) or have “…increases in challenging behavior...” (Ylvisaker, Turkstra, & Coelho, 2005). Cognitively, deficits can include working memory deficits (McDowell et al., 1997; Vanderploeg, Curtiss, & Belanger, 2005; Conklin, Salorio, & Slomine., 2008), decreased attention (Cicerone, 1996; Chan, 2005; Yeates et al., 2005; Mathias & Wheaton, 2007), and deficits in executive functions (“Head”, 1993). Other complications falling within these three categories include lowered processing ability, sleep disturbances, depression, and aggression (Thatcher et al., 2001). Symptoms from a TBI resolve over time dependent on their severity, but most individuals recover within weeks or months. Typically, individuals with more severe initial symptoms take a longer period of time to recover (Nuwer et al., 2005). Regardless of severity, individuals may suffer from severe long-term concerns (Faul et al., 2010).

1.3 TBI Assessment

TBIs are often assessed using clinical measurements such as the Glasgow Coma Scale (GCS), reported symptoms, and neuroimaging techniques (“MTBI”, 2004: Menon et al., 2010) as well with neuropsychological assessments. Although the GSC is frequently and most often used for categorizing severity levels, various studies have formed “mild” and “moderate” TBI groups according to different GSC scores. While some have argued that scores of 13 or higher on the GSC constitute inclusion in the “mild” category others have argued that a score of 13 may fit better in the “moderate” group. Furthermore, the GSC was not intended to be used for diagnostic nor prognostic purposes (Jagoda et al., 2009). In a 10-year study, Balestreri et al. (2004) found that for 358 individuals, GCS significantly correlated with outcome between the years 1992 and 1996 but was no longer a significant predictor of outcome between 1997 and 2001. Another study with 410 individuals reported that GCS score is not strongly correlated with the individual’s 12-month outcome (Foreman et al., 2007). In yet another study that examined mild TBI’s, the authors divided individuals by their GCS score (GSC score of 15 against GCS score of 13 or 14). Though results indicated the 13-14 GCS group exhibited higher amounts of abnormal CT scans, they did not differ in outcome scores on various measures including the Glasgow Outcome Scale and the Rivermead Head Injury Follow-up Questionnaire (McCullagh, Oucherlony, Protzner, Blair, & Feinstein, 2001). Though the GCS does provide some utility in severity diagnosis, previous literature suggests that the GCS is not particularly useful as a measure of outcome.

Another clinical measure of TBI is neuroimaging. Neuroimaging includes various techniques such as computed tomography (CT) scans, magnetic resonance imaging (MRI), and diffusion tensor imaging (DTI); however, these techniques are not always used during clinical assessments as they are not always readily available and are expensive. Additionally, neuroimaging findings are often normal for most incidents of mild TBI (Belanger, Vanderploeg, Curtiss, & Warden, 2007), the most common type of TBI (Faul et al., 2010). In a meta-analysis of 73 studies, Borg et al. (2004) found that most individuals with mild TBI have normal CT scans and, similarly, many patients who exhibit symptoms of mild TBI also have normal MRI scans. Therefore, neuroimaging techniques such as CT scans and conventional MRI scans may not be sensitive enough to detect underlying changes.

Further, substantial research has been conducted on TBI's using neuropsychological assessments. In a meta-analysis of 17 studies regarding mild TBI, Frencham, Fox, and Maybery (2005) found significant deficits in working memory, attention, and processing speed. In a more comprehensive analysis of 39 studies, Belanger et al. (2005) found deficits across many domains including attention, fluency, and executive functions. Importantly, and in line with Frencham et al. (2005), the authors found significantly large deficits in fluency and delayed memory recall. Although long-term outcome following a TBI is inconsistent across severity levels (Yeates et al., 2002) and individuals (Millis et al., 2001), cognitive deficits are still similar across groups regarding domains. For example, a study by Massagli et al. (1996) found deficits in memory, information processing, and academic functioning in children with severe TBI. Yet another study used neuropsychological tests such as the Symbol Digit Modalities Test, Digit Span, and the Trail Making Test, in order to evaluate mTBIs in college athletes. This study concluded that neuropsychological tests are useful for identifying cognitive deficiencies in those with mTBI, and that a full battery assessment would best identify cognitive differences between individuals with TBI. (Echemendia, Putukian, Mackin, Julian, & Shoss, 2001). As evidenced by numerous studies, various neuropsychological measures have repeatedly proven useful in determining cognitive deficits in individuals with TBI.

1.4 Processing Speed Deficits

All of the previously mentioned symptoms of TBI are important; however, slowed information processing speed is the most common (Wozniak et al., 2007; Johansson, Berglund, & Ronnback, 2009). Processing speed is the ability to perform tasks quickly, especially as measured under pressure to maintain attention and concentration (Mather & Wendling, 2014). Many different variations of processing speed tasks have been used to assess general processing speed including decision speed, perceptual speed, psychomotor speed, and time course of internal responses (Salthouse, 2000) A meta-analysis of 41 studies by Mathias and Wheaton (2007) found that participants with severe TBI produced processing speed deficiencies on various measures of both choice reaction time and simple reaction time including the Symbol Digit Modalities Test, the Computerized Tests of Information Processing, Speed of Semantic Processing (from the Speed and Capacity of Language Processing Test), and simple fluency tasks such as generating as many words as possible given a category or as many words as possible given a specific letter. The participants in the studies included in the meta-analysis ranged in time since injury from 59.9 days to 4,937.5 days, exhibiting a large time frame in which deficits could be detected. Another meta-analysis by Belanger et al. (2005) found significant deficits in fluency in the Controlled Oral Word Association Test and the Ruff Figural Fluency Test among participants with mild traumatic brain injury. Additionally, similar results have been found with a group of mild TBI participants who were evaluated within 24 hours of their injury. When compared to a control group with orthopedic injuries, the mild TBI group performed worse on the Speed and Capacity of Language Processing Test (Comerford, Geffen, May, Medland, & Geffen, 2002).

Other studies have found similar results. For example, neuropsychological measures in Thatcher, et al.'s 2001 study included the Weschler Adult Intelligence Scale-Revised (WAIS-R), the Wisconsin Card Sorting Task (WCST), and the Stroop Color-Word Test (Stroop). Various neuropsychological measures were significantly different between the mild and severe TBI groups, such that the authors concluded reduced speed of information processing was most affected by brain injury. Allen, Thaler, Donohue, and Mayfield's (2010) study compared the WISC-IV (Weschler Intelligence Scale for Children-Fourth Edition) to the WISC-III (Weschler Intelligence Scale for Children-Third Edition) and also found that the greatest deficits for children with TBI were on the Processing Speed Index (PSI). This finding also generalized to the WISC-III (Weschler Intelligence Scale for Children-Third Edition) such that children who sustained a TBI had lower scores on the PSI compared to a control group.

Although each of these studies evaluated different severity levels (mild to severe) and evaluated participants at different times post-injury (24 hours to over 10 years), processing-speed repeatedly emerged as a consistent cognitive deficit among those who suffered from a TBI. Consistently, meta-analyses and individual studies have found deficits in processing speed through the use of neuropsychological measures including the WAIS-R, WCST, and Stroop (Thatcher et al., 2001); WISC-III and WISC-IV (Allen et al., 2010); Sternberg Item Recognition Task (Wilde et al., 2011), and various other instruments (Comerfield et al., 2002; Kashluba, Hanks, Casey, & Millis, 2008). Based on this literature, TBI and processing speed deficits should continuously be investigated with neuropsychological measures commonly used in schools, especially as these measures continue to be updated.

1.5 White Matter

One possible explanation for why typical neuroimaging techniques, such as CT and MRI scans, do not always find damage is that CT and MRI scans may not be sensitive enough to find diffuse axonal injuries, an injury that damages white matter tracts, a common occurrence in individuals with TBI (Shenton et al., 2012). However, in an important investigational study, Thatcher, Biver, McAlaster, and Salazar. (1998) investigated the relationship between conventional MRI and EEG coherence. Results indicated that EEG coherence is related to MRI measures of white matter integrity. While participants in the Thatcher et al. (1998) study included a range of mild to severe head injury rather than just mild injuries, the results provide promising support that EEG coherence is related to underlying white matter integrity.

DTI, as opposed to CT and conventional MRI, has shown greater sensitivity to white matter changes than conventional MRI in individuals across varying degrees of TBI severity. Wilde et al. (2006) found lower fractional anisotropy (FA; a measure signifying the integrity of white matter based on the movement of water molecules) in a group of 16 children who sustained moderate to severe TBIs. This group exhibited lower FA in the corpus callosum when compared to uninjured children. Yet another study with 32 children who sustained moderate to severe TBI showed significant reduction/disruption in white matter tracts compared to an orthopedic injury group in the corpus callosum, frontal lobes, and temporal lobes (Levin et al., 2008). In a study by Wozniak et al. (2007), 14 participants between the ages of 10 and 18 with mild to moderate TBI showed significant decreases in FA in inferior frontal, superior frontal, and the supracallosal regions when compared to controls. Finally, Wilde et al., (2011) used DTI to investigate 40 children between the ages of 7-17 who sustained a TBI and compared them to an orthopedic injury group. The authors found the TBI group showed reduced brain volumes in the frontal lobes and the middle frontal gyrus compared to the orthopedic injury group. Furthermore, children with TBI showed cortical thinning in both frontal and temporal lobes, areas typically affected by TBI.

Importantly, DTI studies have also shown that the reduction in white matter is associated with slower processing speed on various tasks. Wilde et al., (2006) found that basic processing speed as measured by reaction time on the Flanker Task was significantly related to mean FA in the splenium of the corpus callosum and in the corpus callosum body. Although there was no significant difference between the TBI group and the typically developing group, a reduction of FA, and therefore lower white matter integrity, was found to be related to slower reaction times. A second study that used the Flanker Task also found processing speed slowed as FA decreased in the frontal cortex and in the corpus callosum (Levin et al., 2008). Another study found that FA in the supracallosal region correlated with processing speed as measured by the Wechsler Adult Intelligence Scale—Third Edition or Wechsler Intelligence Scale for Children—Fourth Edition, such that greater FA is associated with a higher score (Wozniak et al., 2007). Additionally, Wilde et al. (2011) found that slower response times on the Sternberg Item Recognition Task were related to decreased white matter integrity in the left frontal lobe.

As mentioned previously, EEG coherence has been associated with white matter integrity (Thatcher et al., 1998). Given that white matter integrity changes, investigated using DTI, have repeatedly been shown in individuals with TBI who also have processing speed deficits (Wilde et al., 2006; Wozniak et al., 2007, Levin et al., 2008; Wilde et al., 2011), it is important to investigate how EEG coherence relates to individuals with TBI in regards to processing speed.

1.6 EEG and Processing Speed

Results from several studies have demonstrated QEEG measures can significantly discriminate between individuals with a TBI and those without. Thatcher, Walker, Gerson, and Geisler's (1989) study measured brain activity of 264 mild head-trauma patients and 83 controls. From these participants, they derived a discriminant function that was tested with 130 mild head-trauma patients and 21 controls with an accuracy of 96% and 90.5%, respectively. Further cross-validation tests were run to classify between TBI and non-TBI individuals with a 93% accuracy. Overall, the QEEG analysis provided variables that can be applied to signify mild head trauma including increased coherence in frontal and frontal-temporal regions as well as decreased phase in the same areas, reduced alpha power in posterior cortical areas, and decreased power differences between anterior and posterior regions. Further work in QEEG assessment of TBI involved a discriminant function to delineate severity of brain injury between mild and severe, as determined by the Glasgow Coma Scale. A discriminant analysis provided 16 variables within the discriminant function that provided a predictive accuracy of 96% (Thatcher, et al., 2001). Such results indicate that individuals undergo changes in brain activity reflected in EEG after sustaining a TBI; however, while these studies have successfully discriminated between TBI and non-TBI individuals, studies investigating specific cognitive changes in relation to EEG have provided mixed results.

Numerous studies have found negative relationships between coherence and measures of intelligence in populations such as ADHD (Barry, Clarke, McCarthy, & Selikowitz, 2002) and intellectual disability (Martín-Loechesm Muñoz-Ruata, Martínez-Lebrusant, & Gómez-Jarabo 2001). Other studies among the general population have also found similar results (Thatcher, North, & Biver, 2005; Neubauer and Fink, 2009). For example, Thatcher et al. (2005) investigated EEG and intelligence using the Weschler Intelligence Scale for Children revised (WISC-R). Results indicated that EEG absolute power was positively correlated with IQ while coherence was negatively correlated with IQ, although coherence had stronger associations than absolute power. However, several other studies examining coherence and intelligence provides contrasting evidence. Lee et al. (2012) also examined coherence and its relation to general intelligence (*g*) using 6 subtests from the WAIS-III. Results indicated that coherence was related to various cognitive abilities in females such as perceptual reasoning, working memory, and verbal comprehension. Generally, the results indicate a positive relationship between coherence and IQ. Yang, Yang, and Chaou (2010) used the Chinese Wechsler Intelligence Scale for Children III (WISC-III) and also found that coherence was positively related to intelligence. Collectively, these results indicate a large amount of inconsistency in the relationship between EEG and intelligence.

It is well established that processing speed is a cognitive ability related to *g* as described by the Cattell-Horn-Carroll theory of cognitive abilities (McGrew, 2005; Alfonso, Flanagan, & Radwan, 2005; Flanagan, 2013). Similar to the findings regarding general IQ or *g*, inconsistent results also appear when relating EEG to processing speed, although few studies have exclusively investigated this area. A study by Silberstein, Song, Nunez, and Park examined steady state visually evoked potential event related partial coherence (SSVEP-ERPC) and processing speed using the WAIS-III and found processing speed was positively correlated with coherence between electrodes in the right pre-frontal, frontal, and central regions. Yet a study by Lee et al. (2012), also using the WAIS-III, found that coherence was unrelated to processing speed as measured by the symbol search subtest. As evidenced above, the literature relating EEG to intelligence processing speed is minimal and equivocal.

CHAPTER 2

CURRENT STUDY

The current study aims to address 3 areas regarding childhood TBI. First, the current study will investigate neuropsychological performance on a full cognitive battery. As proposed by Echemendia et al (2001), a full battery assessment will be useful for identifying differences among those with TBI. Given the wide range of cognitive impairments that can result from a TBI including working memory (McDowell et al., 1997; Vanderploeg, Curtiss, & Belanger, 2005; Conklin, Salorio, & Slomine., 2008), attention (Cicerone, 1996; Chan, 2005; Yeates et al., 2005; Mathias & Wheaton, 2007), and processing speed (Thatcher et al., 2001; Comerfield et al., 2002; Kashluba et al., 2008; Allen et al., 2010; Wilde et al., 2011), a full cognitive battery rather than select subtests will provide greater insight into potential areas of deficit. The Woodcock Johnson IV (WJ-IV) is the most recent edition of the Woodcock-Johnson assessment system. Revised in 2014, the WJ-IV includes the Tests of Achievement (Schrank, Mather, & McGrew, 2014a) and the Tests of Cognitive Abilities (Schrank, Mather, & McGrew, 2014b). To the best of the author's knowledge, this study is the first to investigate cognitive and academic deficits in childhood TBI using the WJ-IV.

Based on the literature mentioned previously, it is hypothesized that the participants in this study will exhibit deficits on processing speed subtests and the processing speed composite (Gs) as measured by the WJ-IV. The WJ-IV subtests and composites have a mean of 100 and standard deviation of 15. For the purposes of this study, a deficit is considered to be lower than 1 standard deviation below the mean (<85). Additionally, it is hypothesized that a greater percentage of participants than expected will exhibit abnormally low scores, again defined as less than one standard deviation below the mean. This study is the first to use the WJ-IV to investigate processing speed deficits in a sample of school-age children with traumatic brain injuries. Research using the WJ-IV and special populations such as TBI will contribute toward identifying deficits within this population through the use of neuropsychological assessment in order to provide special education services.

The second area this study will investigate is EEG coherence in relation to childhood TBI. Previous literature investigating TBI and white matter integrity found differences in various brain areas including the corpus callosum (Wilde et al., 2006; Levin et al., 2008), frontal regions (Wozniak et al, 2007; Levin et al., 2008; Wilde et al., 2011), and temporal regions (Wilde et al., 2011). EEG coherence has been reported to be a measure of white matter integrity (Thatcher et al., 1998). Therefore, it is hypothesized that differences in EEG coherence will be exhibited among our participants in regions reported in previous literature including frontal and temporal areas.

The third and final area this study will investigate is the connection between EEG coherence values in the alpha and beta bands and their relationship with processing speed on the WJ-IV. As evidenced in previous literature results regarding EEG coherence and TBI have been equivocal. Numerous studies have found a negative relation between coherence and intelligence in different populations (Barry et al., 2002; Thatcher et al, 2005; Neubauer and Fink, 2009); however, other studies have found a positive relation between coherence and intelligence (Yang et al., 2005; Lee et al., 2012). Similarly, studies have found conflicting results between EEG coherence and processing speed. Silberstein (2004) found a positive association between coherence and processing speed. On the other hand, Lee et al. (2012) found no relation. Given the discrepancy in numerous studies regarding EEG coherence, it is hypothesized that alpha and beta coherence values will be able to predict processing speed on the WJ-IV. Alpha and beta bands were chosen as previous literature has suggested that alpha band activity may reflect attentional components while beta activity represents cognitive processes (Rowland, Meile & Nicolaidis, 1985). Additional research has shown that alpha wave activity is also related to memory performance (Klimesch, 1997); however, due to the inconsistent results of previous studies, the direction of such relationships cannot be postulated. Rather, this study aims to contribute to previous literature by providing further evidence. Additionally, this study is the first examine the relationship between the WJ-IV and EEG coherence regarding processing speed deficits.

CHAPTER 3

METHODS

3.1 Participants

Verification of TBI status was obtained by a licensed clinical psychologist certified in brain injury assessment administered a diagnostic intake. Extensive background and diagnostic information was obtained from each participant following referral from their primary care physician. Following intake, each participant was scheduled for testing.

A total of 26 participants were initially tested for inclusion in this study. To be included, participants were required to fall between the ages of 6 and 19 years of age. Additionally, the time from their injury to the testing was not to exceed 3 years. Individuals whose injuries lead to a skull breach were excluded as well as individuals who used illegal drugs. Participants for this study were referred by their primary care doctor for outpatient testing in a psychological clinic in the Southeast of the U.S. The additional participant volunteered to be included in the study. This participant provided documentation from his primary care physician of a TBI that met the criteria of the study. Participants under the age of 18 signed an assent form to participate in the study. Each participant’s guardian signed a consent form. Participants over the age of 18 signed a consent form. Participants signed an additional release of information form from the clinic to allow data to be released to the primary researchers for the purpose of this study.

As a result of the diagnostic intake, 2 participants were excluded. Two additional participants were excluded due to anxiety about the EEG equipment. Progression with the EEG may have compromised their neuropsychogical performance. Finally, equipment malfunctioned for a 5th individual. After the exclusion of these individuals, the study consisted of 21 participants (male, n = 14; female, n= 7) ranging in age between 8.58 and 18.99 years (mean = 14.97). The participants ranged in time since injury to testing from 3 to 36 months (mean = 10.43). Additionally, the participants ranged in injury severity from mild to severe. As not all participants were hospitalized following their injury no consistent reports of severity of their injury, such as the GCS, were provided.

3.2 EEG

Dell laptop and desktop computers were used in the administration, data collection, and data analyses of the EEG recordings. The BrainMaster Discovery amp and program were used to record raw EEG data at a sampling rate of 256Hz. During data collection, a 60Hz notch filter was used to filter out noise due to other electronic devices in the testing room. The BrainMaster Discovery program was selected due to its compatibility with the Neuroguide software program (Thatcher, 2011; Version 2.6.6.4), a separate program used to analyze raw EEG data. Neuroguide (Thatcher, 2011; Version 2.6.6.4) also produces quantitative EEG data (QEEG).

3.3 Procedures

Participants were first fitted with a 19-channel Electro-Cap from Electro-Cap International, Inc. This cap uses the international 10-20 system for electrode placement. Impedance was kept below 10KΩ for all electrodes and for all subjects. Further, ground leads were placed on participants' ears. These leads were kept at or below 10KΩ for all participants. EEG data was collected from participants in both eyes open (EO) and eyes closed (EC) conditions. Each condition was collected twice using three-minute collection periods. For each participant, one EC condition was selected for analyses. Following EEG data collection, participants completed the measures of cognitive and academic abilities

3.4 Cognitive and Academic Measures

Cognitive and academic skills were measured using the Woodcock-Johnson Test of Cognitive Abilities and Tests of Achievement (Schrank. Mather, & McGrew, 2014a; Schrank. Mather, & McGrew, 2014b). The WJ-IV is commonly used by school psychologists for psychoeducational assessments, and consists of subtests that measure various underlying functions as well as academic achievement. The WJ-IV is a standardized test that has been recently revised in 2014 and was designed using the Cattell-Horn-Carroll (CHC) theory of cognitive abilities; As described by Flanagan, Ortiz, & Alfonso (2007) the Woodcock-Johnson tests are the most comprehensive of mainstream intelligence measures as the measure all CHC broad abilities. It is divided into three batteries: Cognitive, Achievement, and Oral Language. The standard battery (subtests 1-10) of the Cognitive battery was administered and includes measures of various cognitive abilities that factor together to form the full-scale IQ score (subtests 1-7). Additionally, Visual-Auditory Learning (subtest 13) and Pair Cancellation (subtest 17) were given. These additional subtests were administered to provide more data for their respective CHC Factors, providing internal validity. These 12 subtests were all given in numerical order and provided composite scores including Comprehension-Knowledge (Gc), Fluid Reasoning (Gf), Short-Term Working Memory (Gwm), Cognitive

Processing Speed (Gs), and Long-Term Retrieval (Glr). Additionally, 6 subtests from the Achievement battery were given. These subtests include Letter-Word Identification (subtest 1), Applied Problems (subtest 2), Passage Comprehension (subtest 4), Calculation (subtest 5), Sentence Reading Fluency (subtest 9), and Math Facts Fluency (subtest 10). The administration of these subtests yielded Reading, Broad Reading, Reading, Mathematics, Broad Mathematics, and Math Calculation Skills composites. These 6 subtests measure reading and math abilities that are important for scholastic achievement. While the Cognitive battery measures underlying cognitive abilities, the Achievement battery measure skills needed to perform well in a school setting. Table 1 provides the name of each WJ-IV cognitive subtest along with its respective composite as well as a brief description of what it aims to measure. Table 2 provides the name of each WJ-IV achievement subtest along with its respective composite and a description of what it aims to measure.

3.5 Statistical Analyses

Standard scores from the WJ- IV Cognitive and Academic subtests and composite scores were used in data analysis. Hypothesis one was tested by comparing the means of the processing speed subtests and composite score to the WJ-IV normative sample mean (mean = 100). Hypothesis two was tested using Crawford, Garthwaite, and Gault's (2007) PercentAbormK program accompanying their article regarding estimating the percentage of low scores. This program requires the number of tests given, the definition of what is considered an abnormally low score (ex: less than 1 SD, less than 1.5 SD, etc.) and the correlation matrix for the subtests. The program then runs one million Monte Carlo trials and provides the percentage of the population expected to have less than a set number of abnormally low scores. These percentages were compared to the number of abnormally low scores exhibited by the TBI participants. For the current study, the test score intercorrelations of ages 14 through 19 were used as the mean age of the participants in this study is 14.97 years.

Before running analyses, all EEG data were inspected visually. A minimum of ten seconds of artifact-free data within the first minute of each sample were selected. This allowed for the use of the drowsiness and eye movement rejection options in Neuroguide (Thatcher, 2011; Version 2.6.6.4). This helped to eliminate artifact from data that followed identifiable patterns due to drowsiness and/or eye movement. Following the removal of artifact, the automatic selection function was used. This function uses the selected artifact-free data as a model to automatically select similar data within the sample. After the removal of artifact, data from EEQ recordings were processed into QEEG metrics through fast-Fourier analysis to determine measurements of alpha, beta, delta, and theta waves within each 3-minute collection period for eyes closed conditions. Neuroguide (Thatcher, 2011; Version 2.6.6.4) includes a normative database of over 600 participants (age range: birth – 82 years), to which the software compares individual EEG records based on the individual's age. This comparison allows for both raw scores and Z-scores. To minimize error, Z-scored coherence was selected rather than raw scores. Additionally, only alpha and beta band Z-scored coherence values were examined.

MATLAB 2007b (Mathworks, Inc.) was used to extract the coherence data from the full dataset. This data was then exported to Microsoft Excel and IBM SPSS Statistics (Version 22.0). Hypothesis three was tested by examining the Z-scores of coherence values. Hypothesis four was tested using linear regression. Given the large number of coherence variables, the current study investigated the coherence values using frontal electrodes (FP1 and FP2) as starting points. Following a factor analysis to reduce the number of EEG coherence variables further, linear regression was run between significant factors and WJ-IV processing speed scores to investigate their relationship.

Table 3.1 Cognitive Subtest Narrow Abilities and Description

Subtest	**Broad CHC Ability**	**Narrow Abilities**	**Description**
Oral Vocabulary	Comprehension-Knowledge (Gc)	Lexical Knowledge Language Development	Consists of two parts: synonyms and antonyms. Together, they measure the ability to semantically associate words presented orally with words similar and different in meaning.
Number Series	Fluid Reasoning (Gf)	Quantitative Reasoning	Measures the ability to determine a missing number from a series of numbers, which involves quantitative reasoning and inductive reasoning.
Verbal Attention	Short-Term Working Memory (Gwm)	Working memory capacity Attentional control	Measures the ability to pay attention to lists of animals and numbers, remember the current list, and answer a question about that list.
Letter-Pattern Matching	Cognitive Processing Speed (Gs)	Perceptual speed	Measures the ability to quickly find two sets of letters in rows of six patterns.
Phonological Processing	Auditory Processing (Ga)	Phonetic coding	Consists of three parts. Substitution measures the ability to replace a phonetic component with another in order to produce a new word. Word Access measures the ability to provide a word that has a specific phonemic component in a set location. Word Fluency measures the ability to quickly retrieve and produce as many words as possible that begin with a specific sound in 1 minute.
Story Recall	Long-Term Retrieval (Glr)	Meaningful memory	Measures meaningful memory and requires the examinee to recall stories presented from an audio recording.
Visualization	Visual Processing (Gv)	Visualization	Consists of two parts. Spatial Relations measures the ability to form a complete shape by choosing smaller pieces from a

			set list. Block Rotation measures the ability to match block patterns to a target pattern and involves a third dimension component
General Information	Comprehension-Knowledge (Gc)	General (verbal) information	Divided into two separate parts. In the Where portion, the subject is asked where they would find a certain object. In the What portion, they are asked what action they would perform with a certain object.
Concept Formation	Fluid Reasoning (Gf)	Inductive reasoning	A controlled-learning task. It measures inductive reasoning and cognitive flexibility, aspects of executive functioning. Specifically, the task requires the child to derive a rule based on a set of visual stimuli.
Numbers Reversed	Short-Term Working Memory (Gwm)	Working memory capacity	Measures the ability to hold a series of numbers in immediate memory and then manipulate those numbers by repeating them to the examiner in backward order.
Visual-Auditory Learning	Long-Term Retrieval (Glr)	Associative Memory	Measures associative memory and requires the examinee to learn, store, and retrieve increasingly complex visual-auditory associations (matching basic drawings with words) to read a story.
Pair Cancellation	Cognitive Processing Speed (Gs)	Attention & Concentration Perceptual Speed Executive Functions	Measures the ability to quickly find a pattern of pictures within a larger set of pictures and involves attention and speed

Table 3.2 Achievement Subtest Narrow Abilities and Description

Subtest	**Cluster**	**Description**
Letter-Word Identification	Reading Broad Reading	Measures word identifications skills. Examinee must read aloud individual words correctly
Applied Problems	Mathematics Broad Mathematics	Measures ability to analyze and solve math problems by listening to a problem, recognize correct procedure to be followed, and perform calculations.
Passage Comprehension	Reading Broad Reading	Measures ability to use syntactic and semantic cues to identify missing word in a text.
Calculation	Mathematics Broad Mathematics	Measures ability to perform mathematical computations including addition, subtraction, multiplication, division as well as some geometric, trigonometric, and calculus operations.
Sentence Reading Fluency	Broad Reading Reading Fluency	Measures reading rate. Requires the examinee to read simple sentences quickly and decide if the statement is true or false.
Math Facts Fluency	Broad Mathematics Math Calculation	Measures speed of computation through the ability to solve simple addition, subtraction, and multiplication facts quickly.

CHAPTER 4

RESULTS

Descriptive statistics including means and standard deviations were calculated for each individual subtest and composite scores. Table 3 provides descriptive statistics for the WJ-IV Tests of Cognitive Abilities. While the Phonological Processing subtest fell in the low average range, all other subtest and composite scores fell in the average range. Of the composite scores, the Cognitive Processing Speed score was the lowest (mean = 93.71). Table 4 provides descriptive statistics for the WJ-IV Tests of Achievement. The Math Facts Fluency subtest fell in the low average range (mean = 88.67) while the remaining subtest and composites fell in the average range. Of the composite scores, the Math Calculation Skills score was the lowest (mean = 91.86). and Table 5 provides the percentage of abnormally low scores estimated using Crawford et al.'s (2007) PercentAbormK program compared to the actual percentage of abnormally low scores of the participants (as determined by less than 1 SD below the mean). Generally, the percentage of TBI participants who had an abnormal number of subtests was consistently above the percentage of the population expected to have the same number of abnormal subtests.

Means and SDs were calculated for each coherence variable in the alpha, and beta bands (n = 70). Table 6 shows the means and SDs of the alpha band while Table 7 shows the means and SDs of the beta band. Overall, no coherence values in the alpha or beta bands were above or below 1 standard deviation of the mean.

All coherence variables were tested for normality using Shapiro-Wilk test of normality. Of the 70 variables, 6 were significant for non-normality ($p < .05$). Negative skews were transformed using the following formula: newvar = 2^{oldvar}. Due to negative z-scored coherence values, negatively skewed data were transformed by adding a constant to the old variable and taking the square root of the result. The constant for each variable was determined by adding .000001 to the absolute value of the lowest coherence value and then adding it to the original value. The square root of this result then represented the new value (constant = |oldvar| +.000001; newvar = sqrt (oldvar + constant). Following transformations, each variable was again tested for normality.

Factors with eigenvalues greater than 1.0 for were extracted for each band (Gorsuch, 1983; Stevens, 1996). For the alpha band this resulted in a 5-factor solution. Table 8 shows the percentage of variance explained for each factor in the alpha band, with a 5-factor solution accounting for over 90% of the variance. Table 9 provides the component matrix and Table 10 shows the rotated component matrix. Variable loadings on each of the 5 alpha components are displayed in Figures 1 through 5. Some variables cross-loaded onto more than one component. In these cases, the component with the greatest loading was selected.

Table 11 shows the percentage of variance explained for each factor in the beta band, with a 5-factor solution accounting for over 89% of the variance. Table 12 provides the component matrix and Table 13 shows the rotated component matrix. Variable loadings for each of these 5 components are displayed in Figures 6 through 10. Similar to the alpha band, some variables cross-loaded onto more than one component and therefore the component with the highest loading was selected.

Following variable reduction, components for each band were entered as a variable regressed onto the processing speed composite score (Gs) using stepwise regression. For the alpha band, component 5 was kept as a significant predictor of Gs, b=.556, $t(15) = 2.916$, $p < .01$. Component 5 also explained a significant proportion of variance in Gs scores, $R^2 = .309$, $F(1,19) = 8.503$, $p < .001$. Table 14 provides the results of the regression analysis for the alpha components. For the beta band, component 3 was kept as a significant predictor of Gs, b=.435, $t(15) = 2.107$, $p <.05$. Component 3 also explained a significant proportion of variance in Gs scores, $R^2 = .189$, $F(1,19) = 4.438$, $p < .05$. Table 15 provides the results of the regression analysis for the beta components.

Table 4.1 Descriptive Statistics-Cognitive

Subtest (Composite)/Composite	*M*	*SD*
Oral Vocabulary (Gc)	100.10	12.153
Number Series (Gf)	102.48	17.907
Verbal Attention (Gwm)	100.71	10.584
Letter-Pattern Matching (Gs)	93.52	13.815
Phonological Processing (Ga)	87.57	10.948
Story Recall (Glr)	95.9	14.405
Visualization (Gv)	99.76	14.359
General Information (Gc)	100.62	12.209
Concept Formation (Gf)	102.62	15.689
Numbers Reversed (Gwm)	97.29	14.506
Visual-Auditory Learning (Glr)	100.9	9.726
Pair Cancellation (Gs)	95.81	11.86
GIA	95.95	11.034
Comprehension-Knowledge	100.71	12.137
Fluid Reasoning	103.48	17.022
Short-Term Working Memory	98.71	11.658
Cognitive Processing Speed	93.71	13.031
Long-Term Retrieval	98.38	11.711

Table 4.2 Descriptive Statistics-Academic

Subtest (Composite)/Composite	*M*	*SD*
Letter-Word Identification	98.14	10.423
Applied Problems	107.43	14.473
Passage Comprehension	98.9	12.186
Calculation	95.81	13.6
Sentence Reading Fluency	96.1	14.373
Math Facts Fluency	88.67	12.419
Reading	98.81	10.255
Broad Reading	97.33	12.431
Mathematics	101	14.128
Broad Mathematics	95.9	12.825
Math Calculation Skills	91.86	11.56

Table 4.3 Percentage of Abnormally Low Subtest Scores (< 1 SD below mean): Expected vs Acquired

Number of subtests	% Population Below	% Participants Below (n=21)
1 or more	68.23	80.95
2 or more	50.35	66.66
3 or more	38.51	42.86
4 or more	30.06	33.33
5 or more	23.65	28.57
6 or more	18.69	19.05
7 or more	14.75	14.29
8 or more	11.58	9.52
9 or more	8.95	9.52
10 or more	6.81	9.52
11 or more	5.05	4.76

Table 4.4 Alpha Band Coherence Descriptive Statistics

Variable	*M*	*SD*
FP1_C3	-0.16636181	1.052946408
FP1_C4	0.02066867	0.903911758
FP1_Cz	0.04588719	0.883489919
FP1_F3	0.251722667	0.816966781
FP1_F4	0.18165219	0.86767206
FP1_F7	0.16766614	0.735384178
FP1_F8	0.19139867	0.891586535
FP1_FP2	0.21590633	0.945760168
FP1_Fz	0.34429871	0.823528014
FP1_O1	-0.05253405	0.796803617
FP1_O2	-0.06812471	0.851576496
FP1_P3	-0.07580352	0.989078602
FP1_P4	-0.02639305	0.75044066
FP1_Pz	-0.108458	0.846169212
FP1_T3	-0.14936924	0.981890693
FP1_T4	0.18188848	0.925504426
FP1_T5	-0.05727652	0.824255254
FP1_T6	-0.02754714	0.838127156
FP2_C3	-0.17536967	1.057192318
FP2_C4	-0.09557624	0.942478954
FP2_Cz	-0.01038395	0.935533695
FP2_F3	0.12934943	0.98431186
FP2_F4	0.19582195	0.91914923
FP2_F7	0.15215429	0.905752166
FP2_F8	0.19341238	0.866018526
FP2_Fz	0.27290743	0.933519016
FP2_O1	-0.08361524	0.812986853
FP2_O2	-0.09801052	0.858353189
FP2_P3	-0.10190081	1.009666341
FP2_P4	-0.12252705	0.72759126
FP2_Pz	-0.13727029	0.851809462
FP2_T3	-0.30470124	1.139361019
FP2_T4	0.16275681	0.827864454
FP2_T5	-0.03884938	0.794612753
FP2_T6	-0.02741438	0.890799303

Table 4.5 Beta Band Coherence Descriptive Statistics

Variable	*M*	*SD*
FP1_C3	0.50273005	0.964978613
FP1_C4	0.44037495	0.974479773
FP1_Cz	0.63278786	0.997973683
FP1_F3	0.40650486	0.905939329
FP1_F4	0.38955519	0.9468152
FP1_F7	0.0849641	0.7326468
FP1_F8	0.25134081	0.782406514
FP1_FP2	0.23987891	0.994097886
FP1_Fz	0.60221	0.905962198
FP1_O1	0.29831495	1.309299099
FP1_O2	0.20752671	1.22675498
FP1_P3	0.15072105	1.024064385
FP1_P4	-0.06355029	0.903168666
FP1_Pz	0.08467957	1.128727965
FP1_T3	0.04678381	0.959876151
FP1_T4	0.18030048	0.788506659
FP1_T5	0.0936769	0.942690263
FP1_T6	-0.39355276	0.843075742
FP2_C3	0.42979543	1.114293
FP2_C4	0.26637071	1.152774848
FP2_Cz	0.49339438	1.18751004
FP2_F3	0.40888795	1.044745293
FP2_F4	0.07706567	1.652589648
FP2_F7	0.27764724	0.786087499
FP2_F8	-0.22975843	1.121364345
FP2_Fz	0.36297352	1.356972025
FP2_O1	0.24530552	1.201483493
FP2_O2	0.02581148	0.99322108
FP2_P3	0.02887205	1.166227725
FP2_P4	-0.07138952	0.926622711
FP2_Pz	0.07183433	1.193826165
FP2_T3	0.00787071	1.136559719
FP2_T4	0.16037691	0.683104483
FP2_T5	-0.07989795	0.902347781
FP2_T6	-0.38234138	0.909469962

Table 4.6 Total Variance Explained by Alpha Band Components

	Initial Eigenvalues			Extraction Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	19.98	57.102	57.102	19.986	57.102	57.102
2	5.333	15.238	72.339	5.333	15.238	72.339
3	3.265	9.329	81.668	3.265	9.329	81.668
4	1.864	5.325	86.993	1.864	5.325	86.993
5	1.231	3.518	90.511	1.231	3.518	90.511
6	.750	2.143	92.655			
7	.665	1.899	94.554			
8	.435	1.243	95.797			
9	.334	.955	96.753			
10	.285	.815	97.568			

Table 4.7 Alpha Band Component Matrix Using Principal Component Analysis

	Component				
	1	2	3	4	5
FP2_F3	.922	-.017	-.241	-.010	-.220
FP2_F7	.921	.011	-.210	.023	-.186
FP2_Fz	.906	.115	-.301	-.006	-.192
FP1_Fz	.904	.040	-.308	-.016	-.179
FP1_F3	.903	-.056	-.195	.075	-.269
FP1_F4	.900	-.060	-.337	-.084	-.069
FP1_F8	.897	.022	-.353	-.139	-.003
FP2_F4	.888	.029	-.279	-.053	-.112
FP1_FP2	.888	.004	-.237	-.058	-.141
FP1_F7	.879	-.065	-.195	.152	-.226
FP2_Cz	.866	-.328	-.181	.056	.048
FP1_Cz	.842	-.388	-.153	.041	.086
FP2_F8	.818	-.009	-.382	-.182	.054
FP2_P3	.787	.094	.465	-.206	-.096
FP1_C4	.762	-.485	.016	-.032	.378
FP2_T3	.751	-.183	.247	.487	-.045
FP1_P3	.747	-.027	.547	-.175	-.070
FP1_T4	.738	-.327	-.064	-.412	.327
FP2_C4	.728	-.509	-.029	.060	.391
FP1_O1	.719	.622	-.031	.068	.060
FP2_C3	.694	-.563	.157	.356	.055
FP2_Pz	.690	-.273	.497	-.153	-.268
FP2_O1	.686	.667	-.117	.076	.075
FP1_T5	.683	.516	.138	-.156	.120
FP2_P4	.651	.048	.625	-.293	-.003
FP1_Pz	.623	-.297	.561	-.152	-.261
FP1_T3	.611	-.342	.305	.585	.049
FP2_T4	.603	-.439	-.128	-.414	.380
FP1_T6	.523	.692	.210	.347	.103
FP1_O2	.601	.669	-.006	.105	.215
FP2_O2	.640	.659	.032	.086	.248
FP2_T5	.614	.621	-.016	-.100	.044
FP1_C3	.922	-.017	-.241	-.010	-.220
FP2_T6	.921	.011	-.210	.023	-.186
FP1_P4	.906	.115	-.301	-.006	-.192

Table 4.8 Alpha Band Component Matrix Using Principal Component Analysis and Varimax with Kaiser Normalization Rotation Method[1]

	Component				
	1	2	3	4	5
FP2_F3	.922	-.017	-.241	-.010	-.220
FP2_F7	.921	.011	-.210	.023	-.186
FP2_Fz	.906	.115	-.301	-.006	-.192
FP1_Fz	.904	.040	-.308	-.016	-.179
FP1_F3	.903	-.056	-.195	.075	-.269
FP1_F4	.900	-.060	-.337	-.084	-.069
FP1_F8	.897	.022	-.353	-.139	-.003
FP2_F4	.888	.029	-.279	-.053	-.112
FP1_FP2	.888	.004	-.237	-.058	-.141
FP1_F7	.879	-.065	-.195	.152	-.226
FP2_Cz	.866	-.328	-.181	.056	.048
FP1_Cz	.842	-.388	-.153	.041	.086
FP2_F8	.818	-.009	-.382	-.182	.054
FP2_P3	.787	.094	.465	-.206	-.096
FP1_C4	.762	-.485	.016	-.032	.378
FP2_T3	.751	-.183	.247	.487	-.045
FP1_P3	.747	-.027	.547	-.175	-.070
FP1_T4	.738	-.327	-.064	-.412	.327
FP2_C4	.728	-.509	-.029	.060	.391
FP1_O1	.719	.622	-.031	.068	.060
FP2_C3	.694	-.563	.157	.356	.055
FP2_Pz	.690	-.273	.497	-.153	-.268
FP2_O1	.686	.667	-.117	.076	.075
FP1_T5	.683	.516	.138	-.156	.120
FP2_P4	.651	.048	.625	-.293	-.003
FP1_Pz	.623	-.297	.561	-.152	-.261
FP1_T3	.611	-.342	.305	.585	.049
FP2_T4	.603	-.439	-.128	-.414	.380
FP1_T6	.523	.692	.210	.347	.103
FP1_O2	.601	.669	-.006	.105	.215
FP2_O2	.640	.659	.032	.086	.248
FP2_T5	.614	.621	-.016	-.100	.044
FP1_C3	.922	-.017	-.241	-.010	-.220
FP2_T6	.921	.011	-.210	.023	-.186

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[1] Rotation converged in 8 iterations

FP1_P4	.906	.115	-.301	-.006	-.192

Table 4.9 Total Variance Explained by Beta Band Components

	Initial Eigenvalues			Extraction Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	21.763	62.181	62.181	21.76	62.181	62.181
2	4.644	13.268	75.448	4.644	13.268	75.448
3	2.278	6.508	81.956	2.278	6.508	81.956
4	1.575	4.499	86.455	1.575	4.499	86.455
5	1.138	3.251	89.706	1.138	3.251	89.706
6	.946	2.703	92.409			
7	.632	1.806	94.215			
8	.609	1.739	95.954			
9	.370	1.056	97.010			
10	.248	.707	97.718			

Table 4.10 Beta Band Component Matrix Using Principal Component Analysis

	Component				
	1	2	3	4	5
'B_FP2_C3'	.938	-.182	.061	-.031	-.239
'B_FP1_Cz'	.930	.045	.033	-.081	-.212
'B_FP1_F4'	.924	.088	-.231	-.005	-.103
'B_FP2_Cz'	.919	-.063	-.135	.185	-.212
'B_FP1_F3'	.916	.082	-.250	-.044	-.073
'B_FP1_Fz'	.913	.120	-.286	.007	-.144
'B_FP2_F7'	.907	-.034	-.173	.050	.078
'B_FP1_C4'	.903	-.124	.068	-.255	-.197
'B_FP2_C4'	.898	-.212	-.104	-.008	-.204
'B_FP2_F3'	.895	-.066	-.264	.195	-.091
'B_FP1_C3'	.878	-.101	.126	-.294	-.238
'B_FP1_F8'	.868	.174	-.203	-.078	.133
'B_FP1_T4'	.866	-.077	.113	-.159	.068
'B_FP2_Pz'	.862	-.312	.336	-.055	-.112
Trans_B_FP2_Fz	.854	-.034	-.267	.329	-.043
'B_FP2_T4'	.853	-.189	-.102	-.013	.145
Trans_B_FP2_F4	.848	-.088	-.288	.278	-.002
'B_FP2_P4'	.831	-.436	.134	.038	.143
'B_FP1_Pz'	.831	-.265	.399	-.207	-.080
Trans_B_FP2_F8	.817	-.066	-.405	.051	.313
'B_FP2_T6'	.813	.217	.193	-.098	.423
Trans_B_FP1_FP2	.812	-.127	-.454	-.007	.113
'B_FP1_P4'	.806	-.395	.190	-.097	.183
'B_FP2_P3'	.789	-.374	.327	-.042	-.056
'B_FP1_P3'	.725	-.416	.326	-.255	.046
'B_FP1_T5'	.684	.459	.185	.294	.078
'B_FP1_F7'	.671	.099	-.338	-.350	.339
'B_FP2_T3'	.648	-.052	.503	.511	-.031
'B_FP1_T3'	.558	-.129	.496	.432	.320
Trans_B_FP1_O2	.302	.842	.151	-.195	-.094
'B_FP1_O1'	.509	.798	.123	.056	-.108
'B_FP2_O1'	.478	.797	.063	.071	-.124
'B_FP2_O2'	.469	.752	.168	-.252	-.101
'B_FP2_T5'	.585	.632	.070	.351	.046
'B_FP1_T6'	.502	.582	.191	-.309	.341

Table 4.11 Beta Band Component Matrix Using Principal Component Analysis and Varimax with Kaiser Normalization Rotation Method[2]

	Component				
	1	2	3	4	5
Trans_B_FP1_FP2	.866	.290	.043	.005	.239
Trans_B_FP2_F4	.847	.291	.109	.270	.017
Trans_B_FP2_Fz	.846	.273	.164	.305	-.039
'B_FP2_F3'	.844	.376	.169	.196	-.023
Trans_B_FP2_F8	.839	.223	.079	.142	.396
'B_FP1_Fz'	.816	.388	.365	.016	.017
'B_FP1_F4'	.783	.431	.348	.051	.057
'B_FP1_F3'	.781	.428	.336	.021	.099
'B_FP2_Cz'	.773	.487	.222	.213	-.131
'B_FP2_F7'	.746	.436	.215	.186	.187
'B_FP2_C4'	.700	.626	.106	.083	-.055
'B_FP1_F8'	.694	.352	.391	.073	.292
'B_FP2_T4'	.653	.512	.069	.191	.255
'B_FP1_F7'	.585	.257	.233	-.170	.566
'B_FP1_Pz'	.259	.913	.143	.198	.099
'B_FP2_Pz'	.364	.865	.086	.284	.014
'B_FP1_P3'	.231	.864	-.054	.154	.215
'B_FP2_P3'	.326	.824	-.005	.296	.046
'B_FP1_C3'	.453	.808	.280	-.052	.020
'B_FP1_C4'	.519	.778	.247	-.028	.047
'B_FP1_P4'	.412	.740	-.071	.277	.293
'B_FP2_C3'	.607	.739	.186	.138	-.079
'B_FP2_P4'	.504	.699	-.120	.349	.207
'B_FP1_T4'	.473	.659	.243	.150	.240
'B_FP1_Cz'	.593	.641	.386	.083	-.026
Trans_B_FP1_O2	.001	.015	.927	-.086	.063
'B_FP1_O1'	.225	.046	.924	.138	-.024
'B_FP2_O2'	.096	.186	.909	-.083	.099
'B_FP2_O1'	.250	-.005	.901	.109	-.045
'B_FP2_T5'	.389	-.021	.737	.421	.001
'B_FP1_T6'	.083	.207	.720	.054	.516
'B_FP1_T5'	.373	.183	.637	.473	.055
'B_FP1_T3'	.137	.391	.080	.812	.157

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[2] Rotation converged in 8 iterations

'B_FP2_T3'	.220	.467	.217	.770	-.175
'B_FP2_T6'	.365	.441	.459	.334	.534

Table 4.12 Alpha Component Predictors of Gs

Variable	B	SE (B)	*β*	*R*	R^2
(Constant)	93.714	2.425			
Component 5	7.246	2.485	.556*	.556	.309

Table 4.13 Beta Component Predictors of Gs

Variable	B	SE (B)	*β*	*R*	R^2
(Constant)	93.714	2.627			
Component 3	5.671	2.692	.435*	.435	.189

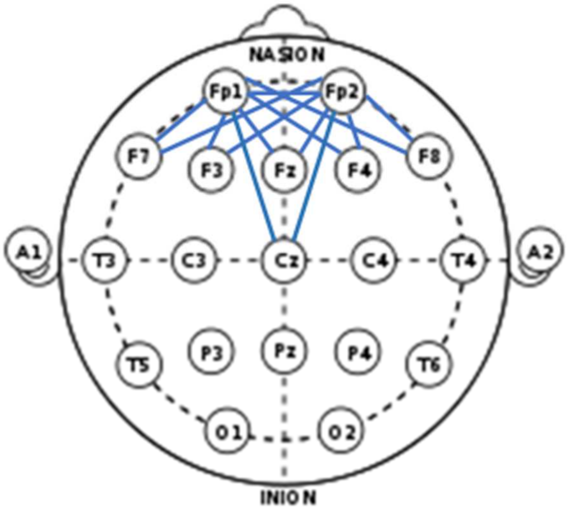

Figure 4.1 Alpha: Rotated component 1

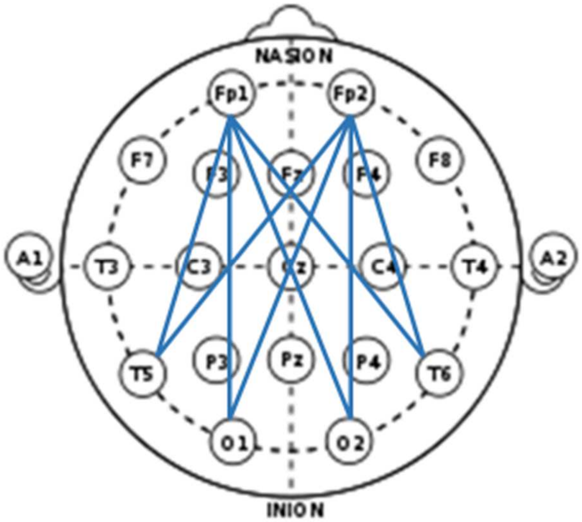

Figure 4.2 Alpha: Rotated component 2

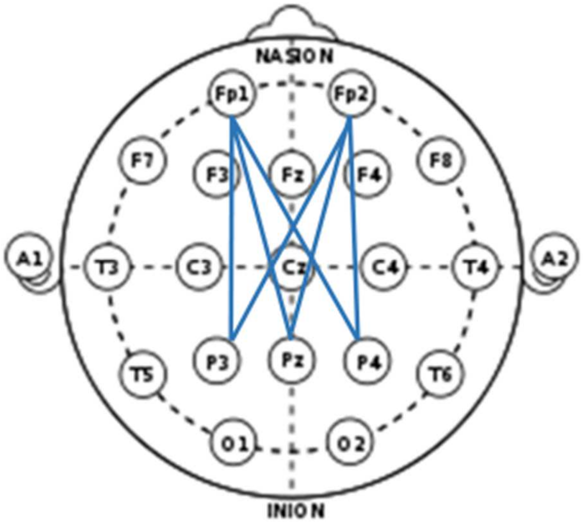

Figure 4.3 Alpha: Rotated component 3

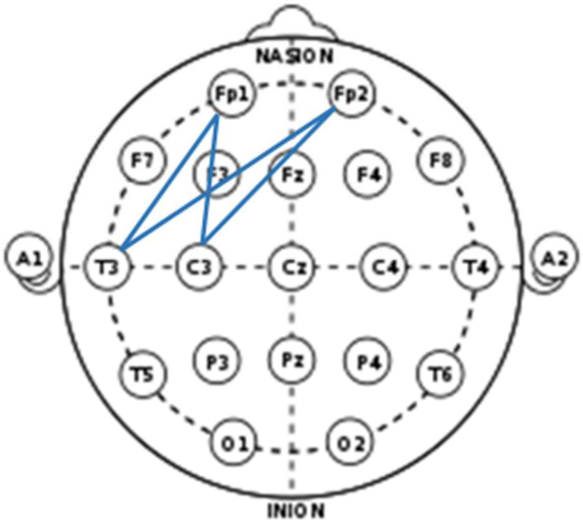

Figure 4.4 Alpha: Rotated component 4

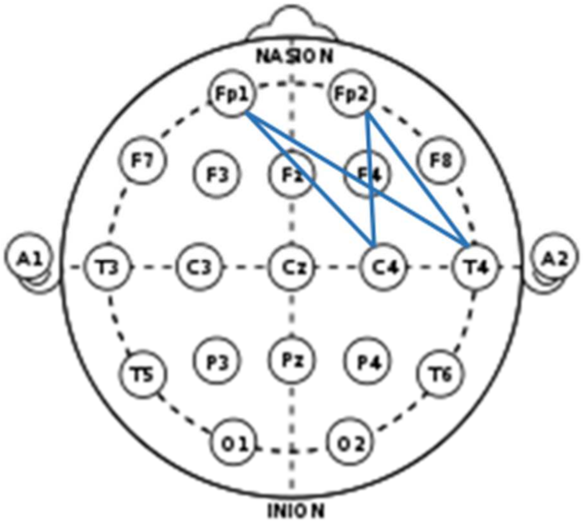

Figure 4.5 Alpha: Rotated component 5

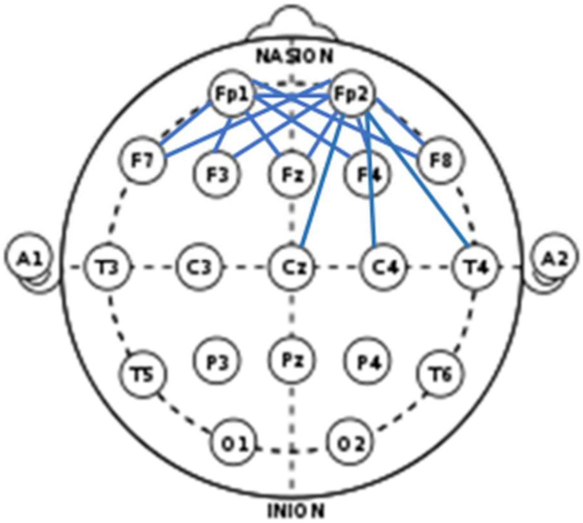

Figure 4.6 Beta: Rotated component 1

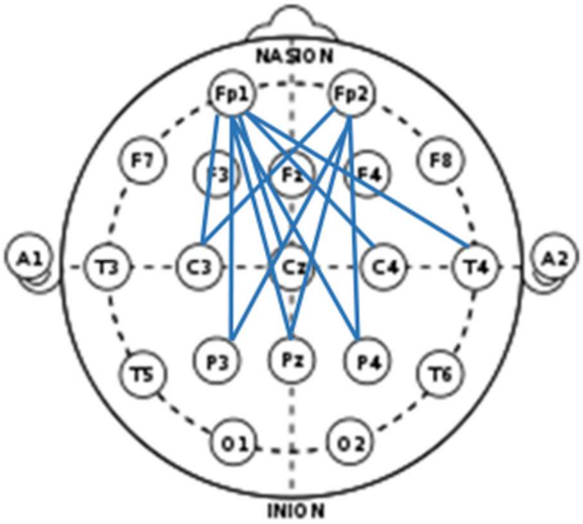

Figure 4.7 Beta: Rotated component 2

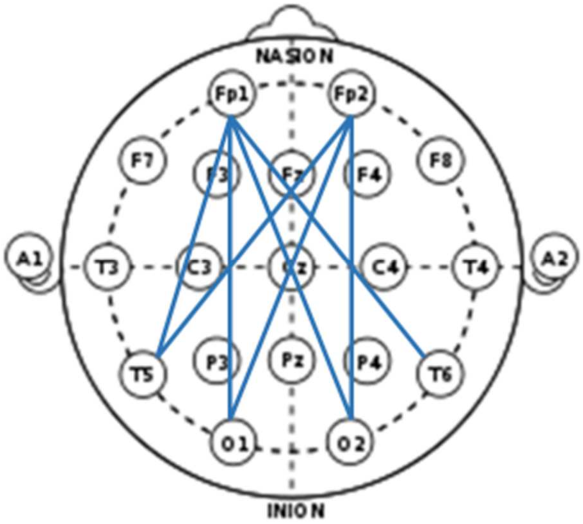

Figure 4.8 Beta: Rotated component 3

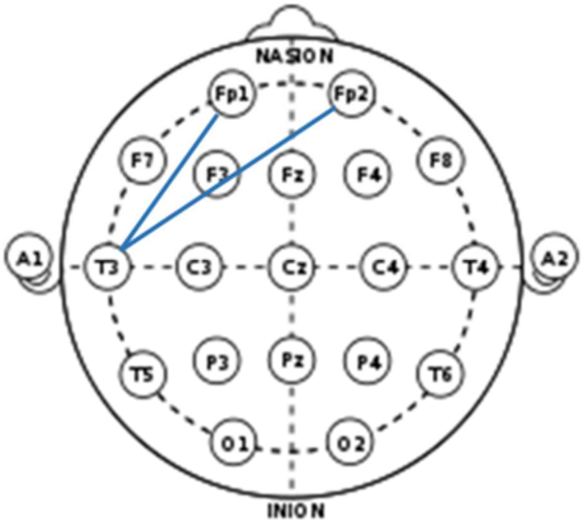

Figure 4.9 Beta: Rotated component 4

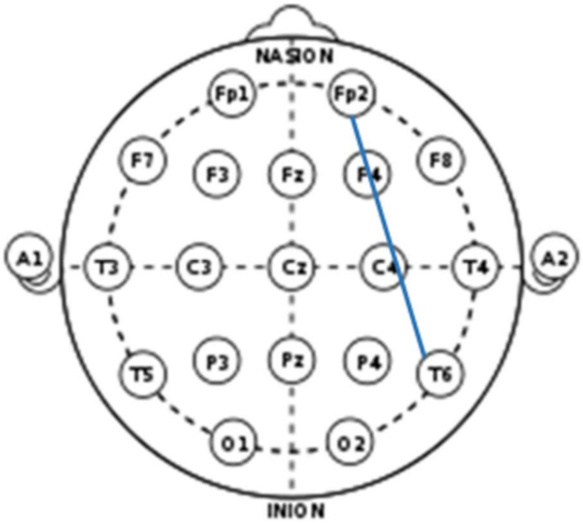

Figure 4.10 Beta: Rotated component 5

CHAPTER 5

DISCUSSION

5.1 Discussion

The purpose of this study was to investigate the cognitive and academic deficits in children who sustained a TBI as measured by the WJ-IV as well as the underlying neurological associations as measured by EEG. Understanding these deficits is imperative as school psychologists begin to use the WJ-IV, the most recent version in the series of Woodcock-Johnson assessments, to assess students for eligibility services. Specifically, this study investigated the effects of TBI on processing speed, a common deficit seen in those who sustained a TBI, and general cognitive deficits. Additionally, this study sought to understand how EEG coherence changes within this population and, further, investigate the association between EEG coherence and processing speed.

Regarding the first hypothesis, the results of this study did not find processing speed deficits on any measure of processing speed on the WJ-IV Tests of Cognitive Abilities or on any fluency measures on the WJ-IV Tests of Achievement. As displayed in Table 3 and Table 4, Letter-Pattern Matching ($M = 93.52$), Pair Cancellation ($M = 95.81$), Cognitive Processing Speed Composite ($M = 93.71$), and Sentence Reading Fluency ($M = 96.1$) all fell in the average range; however, as displayed in Table 4, Math Facts Fluency ($M = 88.67$) fell in the low average range. These findings are inconsistent with previous research that utilized measures of cognitive and academic abilities (Echemendia et al., 2001; Thatcher et al., 2001; Frencham et al., 2005; Belanger et al., 2005; Allen et al., 2010), although Math Facts Fluency approaches the pre-determined cutoff to be considered a deficit. One potential reason for these findings is that severity of injury can affect outcomes. For example, Comerford et al. (2002) found processing speed deficits in a mild TBI group when tested within 24 hours of their injury and Mathias, Beall, and Bigler (2004) found reductions in reaction time tasks in a mild TBI group after one month. Another study by Tombaugh et al., (2007) measuring reaction time found that severity of injury resulted in an increase in reaction time. Further, a study by Rassovsky et al. (2006) found that processing speed mediated the relationship between TBI severity and adaptive functioning at 12 months after injury. Generally, long-term outcome after a TBI is variable across severity levels (Yeates et al., 2002). Such literature suggests two ideas; first, the more severe the TBI, the larger the deficit; and two, the more severe the TBI, the longer the deficit lasts. Therefore, given the range in which the participants in this study were assessed post-injury (range: 3 to 36 months; mean = 10.43 months), it is possible that individual participants processing speed deficits had been resolved by the time of assessment.

Though the participants in the study were not found to have processing speed deficits, results indicated general deficits across all subtests below what would be expected of a general population, providing support for the second hypothesis. As displayed in Table 5, the number of participants who had abnormally low scores on a given number of subtests (<1 SD below the mean) was repeatedly below what would be expected in the general population. These results suggest that children who suffered from a TBI can be expected to display deficits in various cognitive and academic abilities more regularly than the general population. For instance, individual participants tended to score low on the measures of processing speed, phonological processing, math fluency, and calculation; however, similar to the hypothesis one, these results may be influenced by the interval between injury and assessment. For example, mild TBI individuals may display more cognitive and academic deficits when assessed closer to injury while more severe injuries may result in chronic deficits that can be seen at later time points.

Although previous literature revealed increased coherence in frontal and frontal-temporal regions in participants with TBI (Thatcher et al., 1989), results from the current study did not reveal significant deficits or surpluses in coherence in these region, although these regions did produce the highest and lowest values. For example, the lowest z-scored coherence pairings in the Alpha band were between the frontal electrodes and the left temporal areas while the highest z-scored coherence pairings were in the frontal regions. For the Beta band, the lowest z-scored coherence pairings were between the frontal electrodes and the right temporal and right frontal electrodes while the highest pairings were between the frontal electrodes and central electrodes; however, no single coherence pairing in the Alpha or Beta band was more than one standard deviation above or below the mean. While the scores did not appear to support the hypothesis, the regions in which the highest and lowest scores are commensurate with earlier literature regarding white matter integrity differences in individuals with TBI (Wozniak et al., 2007; Levin et al., 2008; Wilde et al., 2011).

Finally, the regression results provide support for the fourth hypothesis. Following the reduction of variables, the regression of the component variables on processing speed revealed significant results in both the Alpha and Beta band. Component 5 in the Alpha band significantly predicted the Processing Speed composite score as measured by the WJ-IV such that the greater the coherence score, the greater the processing speed score. As can be seen in Figure 5, Component 5 is comprised of coherence values between the frontal and right temporal regions. This provides support for previous work that has examined coherence and processing speed measures and found both a positive relationship and a relationship in similar areas (Thatcher et al., 1989; Silberstein et al., 2004) while simultaneously contrasting previous efforts that found no relation between EEG and processing speed (Lee et al., 2012). Component 3 in the Beta band also significantly predicted processing speed, such that the greater the coherence score the greater the processing speed score. As can be seen in Figure 8, this component is comprised of frontal to occipital and frontal to temporal regions. This too provides support for similar relationships but also presents an interesting finding in the connection between Frontal and Occipital regions. Taken together, these findings suggest that EEG coherence values, as measures of white matter integrity, are significantly related to the processing speed composite score on the WJ-IV, a psychometrically sound measure. These promising results could lead to future validity checks using both the WJ-IV and EEG. For example, it is possible that an individual's processing speed scores could be predicted using EEG and later validated through a neuropsychological assessment such as the WJ-IV. Consider an individual who sustained a TBI and is returning to school after being hospitalized. TBI individuals have been found to have poor sustained attention (Dockree et al., 2006), and the administration of a neuropsychological test battery may take hours. Rather, an EEG can be administered, artifacted, and interpreted in a relatively short amount of time that can provide reliable information regarding potential deficits.

5.2 Limitations and Future Directions

Though the current study has many strengths, such as an age range spanning school ages and using a clinical sample of TBI participants, there are a few limitations. First, the study did not include a control group to compare to the TBI group. This significantly limited the comparisons and conclusions that could be drawn based on the data collected. For instance, although processing speed and fluency scores of the TBI group were not below the one standard deviation cut off, it is possible that once collected, the TBI group might different significantly on these or other measures. This led to the use of the PercentAbormK program to test the second hypothesis. While this method provided some insight into what may be expected of a normative population compared to the TBI group, it cannot replace the value of an age-matched control group and the subsequent comparisons that could be made. Additionally, the use of the PercentAbnormK program cannot test group differences in specific subtests such as the processing speed subtests, and therefore limits comparisons to performance across all subtests. Future studies should include an age-matched control group to make comparisons between TBI and non-TBI individuals

Another limitation is the use of only two EEG bands. Although the Alpha and Beta bands were chosen based on previous literature and their implications in attention and cognitive processing, this study did not include other Bands including Delta and Theta bands. Furthermore, the current study only looked at coherence pairings using the frontal electrodes. Again, these electrodes were chosen based on previous literature that focused on frontal, front-temporal, and temporal regions. Additionally, due to the number of participants in the study it was essential that the number of electrode pairings be reduced to increase effect size. In future studies, more participants should be included so that other bands and other electrode pairings both within and across regions can be assessed.

A final limitation is the lack of severity ratings for participants. Severity of TBI can be highly influential in understanding recovery and presentation, and it is quite possible that some of the results of this study were muddled due to the lack of clarification and separation of mild and severe incidents of TBI. Unfortunately, consistency across participants was not available due to the nature of recruitment for the study. Not all participants were hospitalized, where the GCS is commonly used to assess severity. Additionally, not all participants sought medical treatment immediately after their injury or did not seek treatment at all. Still others sought treatment but delayed cognitive and academic testing. Obtaining a consistent measure of severity would enable statistical control of that variable to determine whether severity did or did not play a role in the findings.

5.3 Conclusion

The effects of TBIs among children are highly irregular. Age, severity, time between injury and assessment, and many other variables can affect both the cognitive and academic outcomes as well as underlying brain functioning. Neuroimaging measures can be expensive and are not always available; therefore, newer and cheaper but also valid and reliable measures of brain functioning must be explored. As new cognitive measures, such as the WJ-IV, are designed and used by practitioners both inside of schools outside of schools, it is important that they understand the profiles of children who suffer from a TBI as these profiles can help inform treatment, recovery, and determine eligibility status for special education services in schools.

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