Brigham Young University
BYU ScholarsArchive

Theses and Dissertations

2013-05-30

Error Processing and Naturalistic Actions Following Moderate-to-Severe Traumatic Brain Injury

Daniel A. Good
Brigham Young University - Provo

Follow this and additional works at: https://scholarsarchive.byu.edu/etd

 Part of the Psychology Commons

BYU ScholarsArchive Citation

Good, Daniel A., "Error Processing and Naturalistic Actions Following Moderate-to-Severe Traumatic Brain Injury" (2013). *Theses and Dissertations*. 3804.
https://scholarsarchive.byu.edu/etd/3804

This Dissertation is brought to you for free and open access by BYU ScholarsArchive. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of BYU ScholarsArchive. For more information, please contact scholarsarchive@byu.edu, ellen_amatangelo@byu.edu.

Error Processing and Naturalistic Actions Following Moderate-to-Severe Traumatic Brain Injury

Daniel A. Good

A dissertation submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

Michael J. Larson, Chair
Scott A. Baldwin
Patrick R. Steffen
Edwin E. Gantt
Mikle D. South

Department of Psychology

Brigham Young University

October 2013

Copyright © 2013 Daniel A. Good

All Rights Reserved

ABSTRACT

Error Processing and Naturalistic Actions Following
Moderate-to-Severe Traumatic Brain Injury

Daniel A. Good
Department of Psychology, BYU
Doctor of Philosophy

Moderate-to-severe traumatic brain injury (M/S TBI) can affect an individual's ability to perform daily tasks. For example, individuals with M/S TBI are more likely to commit errors on tasks such as making a meal or wrapping a present. The neural processes involved in such errors are poorly understood. Studies suggest that neurophysiologic markers of cognitive control and error processing may be helpful in gaining additional insight into errors on naturalistic action tasks. Unfortunately, previous experimental methods left a methodological gap which limited the use of neurophysiological markers in the study of naturalistic action. Several recent studies in healthy adults have suggested one method of bridging the gap by having individuals observe another person's errors. The current study was the first study to employ the method in a TBI population as a possible means of gaining additional insight into the detrimental effects of M/S TBI on the performance of naturalistic actions. In order to gain additional insight into the effects of M/S TBI on the completion of naturalistic tasks I used two neurophysiologic markers of cognitive control and error processing. They were the observer error related negativity (oERN) and the P300 components of the scalp-recorded event-related potential (ERP). I hypothesized that individuals with M/S TBI would demonstrate error-specific changes in the two oERN and P300 that would correlate with self-reported difficulties in daily functioning. The study consisted of two experiments. One compared 15 individuals with M/S TBI to 17 demographically similar healthy controls on an error related naturalistic action based picture task. The second compared an overlapping sample of 16 individuals with M/S TBI to 16 demographically similar controls as they watched a confederate complete the Erikson flanker task, a commonly used task in the study of electrophysiological markers. Accuracy (error vs. correct) and group (M/S TBI vs. control) effects were analyzed using 2 x 2 repeated measures ANOVAs on ERP amplitude and latency. Pearson product-moment correlations were calculated to evaluate the relationship between the P300 and oERN and measures of self-reported executive functioning (Frontal Systems Behavior Scale, FrSBe) and neuropsychological measures. Findings supported a difference between the control and M/S TBI groups in how errors were processed during the naturalistic actions based picture task. There was an interaction between group membership and response accuracy (error vs. correct) on P300 amplitude and P300 latency. Controls demonstrated reduced P300 amplitude and latency on error trials compared to correct trials. Individuals with M/S TBI did not demonstrate a significant difference between correct trials and error trials on P300 amplitude and latency. The amplitude and latency of the P300 were correlated with self-reported functional difficulties in individuals with M/S TBI but not control participants. A Fisher's r – z analysis indicated that correlations differed significantly between groups; however, an outlier was identified in the correlational data. Removal of the outlier data led to non-significant results in the Fisher's r – z analysis. Taken together, results of the picture task supplied evidence that for individuals with M/S TBI differences in neurophysiologic markers between groups could be explained by reduced

adaptation to complexity or by possible deficits in a secondary error processing pathway for complex errors. Future research could focus on better defining the functional relationship between P300 amplitude and latency and increased errors in naturalistic actions following M/S TBI. Observation of the flanker task did not elicit oERN waveforms from either healthy controls or from individuals with M/S TBI. The results could be due to problems with the current task, but also raised some concerns about previous studies using the flanker task which employed a slightly different methodology requiring participants to count errors. The current study did not require participant to count errors. As a whole, the study supplied partial support for using electrophysiological markers of error processing to gain additional understanding increased errors in the performance of naturalistic actions following M/S TBI.

Keywords: electrophysiology, event related potentials, error related negativity, oERN, P300, traumatic brain injury, error processing, performance monitoring

ACKNOWLEDGEMENTS

I would like to give special appreciation to the members of Dr. Michael Larson's Clinical Cognitive Neuroscience and Neuropsychology laboratory. Specifically, I would like to thank Melissa Woodhouse and Brendan Abbott for their tireless efforts and frequent weekends in collecting data and interacting with participants. I would also like to acknowledge Joseph Fair for his contributions in in all aspects of the current study. A special thank you is merited to Dr. Michael Larson for his patience, dedication, availability, and counsel during the completion of this work. Finally I would like to express gratitude to my wife and family for their support, patience, and willingness to shoulder a tremendous load so that I could focus my efforts on the work presented below. Thank you all for your efforts.

.

Table of Contents

List of Tables

List of Figures

Error Processing and Naturalistic Actions Following Moderate-to-Severe Traumatic Brain Injury

Naturalistic activities are a type of behavior that, as opposed to many tasks used in laboratory settings, are often complex and similar to independent goal-directed activities completed during daily living. Naturalistic actions generally consist of intricate interdependent goals and sub-goals that must be organized, prioritized, and monitored for correct completion (Cook, Chapman, & Levin, 2008; Schwartz et al., 1998). Examples of naturalistic actions include making a sandwich or driving to work. Several studies indicate that individuals with moderate-to-severe traumatic brain injury (M/S TBI) show difficulties performing naturalistic actions correctly (Buxbaum, Schwartz, & Montgomery, 1998; Hart, Giovannetti, Montgomery, & Schwartz, 1998; Jung, Kim, Kang, & Kim, 2013; Schwartz et al., 1998). For example, Schwartz et al., (1998) found that individuals with TBI performed significantly worse than controls on relatively simple naturalistic tasks such as brewing coffee, wrapping a present, and packing a lunch. In the study, 16 individuals with TBI committed a total of 299 errors on the naturalistic tasks (summed across all participants) with 38% of errors classified as errors of omission (leaving out important steps), 20% classified as errors of sequencing (such as stirring the hot water before pouring in coffee grinds), and 12% of errors classified as action additions (cutting the gift box or placing extra items in the lunch box). In contrast, the control group of 18 individuals committed a total of 36 errors with one individual committing seven of those errors. Of the control group errors, 31% were errors of sequencing and 19% were action additions. Errors of omission accounted for only 3% of errors in the control group. The findings suggested

individuals with TBI have considerable difficulty completing naturalistic tasks and make more frequent mistakes than their healthy counterparts.

The neurologic mechanisms that contribute to recorded differences in the number and type of errors committed by individuals with TBI are not yet completely understood. Effective rehabilitation of error commission following M/S TBI could be improved with an accurate and detailed understanding of the neurologic mechanisms involved. Such an understanding would allow researchers to specifically target their efforts towards those mechanisms. The end goal would be the development of rehabilitation strategies or medical interventions to correct the deficits defined as contributory to naturalistic action errors. One possible method of gaining increased understanding of the neurological changes involved in naturalist action errors following M/S TBI is the use of neurophysiological markers of cognitive control and error processing.

Cognitive control refers to the ability to regulate and then evaluate behavior so that behaviors correspond with internal goals (Botvinick, Carter, Braver, Barch, & Cohen, 2001; Miller & Cohen, 2001). Accepted theory about cognitive control suggests that human cognition is supported by multiple parallel processes occurring throughout the brain using similar neurons and anatomical regions (Desimone & Duncan, 1995). Allport (1987) suggested that much of the functional limitations observed in working memory, attention, or other cognitive processes could be explained by cross interference between overlapping processes using similar neuronal hardware. These parallel processes included sensations, perceptions, emotions, behavioral options, and all other neural processes (Miller & Cohen, 2001). For example, when confronted with a situation that requires action, all identified options for response are activated and processed in parallel fashion throughout the brain. In order to select one of the multiple

behavioral options cognitive control is implemented to choose the option consistent with the internal goal and suppress the options inconsistent with that goal.

In two widely cited papers, Miller and Cohen (2001) and then Botvinick, Carter, Braver, Barch, and Cohen (2001) proposed a theory of how the various aspects of cognitive control function. Botvinick et al. (2001) suggested that cognitive control is divided into two component processes, a regulative component and an evaluative component. The regulative component of cognitive control applies top down regulation of control through biasing of neural networks in order to facilitate the implementation of goal directed behaviors (Miller & Cohen, 2001). The regulative component of cognitive control is likely a widely distributed process that occurs throughout the brain, but has a focus within the prefrontal cortex (PFC). The evaluative component of cognitive control serves to detect when there are errors or discrepancies in achieving goal directed actions and to direct the application of regulative control to overcome such errors or discrepancies. For example, Botvinick et al. (2001) proposed that the evaluative component is activated by cross interference or conflict between processes (conflict monitoring) in the parallel network. The evaluative component of cognitive control also compares executed behavior with intended behavior and signals regulative areas, such as the PFC, to apply increased control (Botvinick et al., 2001). For instance, when asked to push a button during a response-inhibition task multiple possible behaviors are processed at the same time such as pushing the button or inhibiting the inappropriate response. Interference between possible behaviors would activate the evaluative component of cognitive processing which might signal for increased regulative control to improve the likelihood of a correct response inhibition. Recent work has suggested that the anterior cingulate cortex (ACC) plays an important role in the evaluative component of cognitive control (Botvinick, Cohen, & Carter, 2004; Holroyd & Coles, 2002;

Kerns et al., 2004; Yeung, Botvinick, & Cohen, 2004; Yeung & Nieuwenhuis, 2009). The ACC has been shown to activate in the presence of conflict or errors and then signal the PFC for subsequent adjustments in high conflict tasks such as the Stroop task or the Eriksen flanker task (e.g., Kerns et al. 2004).

Injuries to anatomical systems related to cognitive control are common following M/S TBI. For example, during TBI injury to the ACC may be relatively common despite its apparently protected position in the depths of the longitudinal fissure (Stamatakis, Wilson, Hadley, & Wyper, 2002). The proximity of the ACC to the ridged surface of the falx cerebri (a rigid support membrane along the vertical midline of the brain) places it at risk for compression and grating (Gean, 1994). In addition, the cingulum bundle, a group of white matter fibers that courses the length of the cingulate gyrus, is vulnerable to axonal injury (Bendlin et al., 2008; Kraus et al., 2007; Rutgers et al., 2008; Wu et al., 2010). The ACC is also vulnerable to secondary effects related to a loss of incoming and outgoing connections with other brian regions caused by tearing of white matter tracks during TBI (Bigler, 2007). Damage to the frontal lobes, especially the orbital frontal and lateral PFC, is one of the more common injuries following TBI (Bigler, 2005) due to their proximity to bony protuberances near the sinuses within the frontal portion of the skull.

The effects of damage to prefrontal- and cingulate-mediated cognitive control systems are still being documented but appear to reduce an individual's ability to affectively apply cognitive control. Swick and Turken (2002) presented a case study of an individual with a focal ACC lesion. The individual named R.N. was able to perform a simple experimental task similar to controls, but his ability to accurately correct his mistakes was significantly poorer than controls. Damage to the PFC is associated with impairment on tasks related to executive control

or when top-down processing is needed to organize high conflict behaviors around goals and maintain goals online (Blakemore & Robbins, 2012; Fleming & Dolan, 2012; Løvstad et al., 2012; Miller & Cohen, 2001). One particular difficulty seen following damage to the cognitive control system is that of detecting errors and adjusting behaviors following errors or conflict (see Larson et al., 2009 for review).

Researchers have identified neurophysiological markers related to error processing and cognitive control which can be observed while measuring the brains electrical signals (e.g., Brazil et al., 2009; Carter et al., 2000; de Bruijn, Schubotz, & Ullsperger, 2007; Olvet & Hajcak, 2009; Overbeek, Nieuwenhuis, & Ridderinkhof, 2005). Individuals with M/S TBI demonstrate severity-dependent changes in neurophysiologic markers of cognitive control and error processing which correlate with behavioral changes such as reduced awareness of errors (Larson, Kaufman, Schmalfuss, & Perlstein, 2007; Larson & Perlstein, 2009). Deficits in cognitive control following M/S TBI appeared to exist either in addition to or independent of more generalized cognitive impairment (Levine, Katz, Dade, & Black, 2002; Perlstein et al., 2004).

The goal of the current study was to extend our understanding of the phenomena of increased naturalistic errors following M/S TBI through the use of neurophysiologic marker of cognitive control and error processing. To accomplish the goal I used a relatively new manipulation for eliciting neurophysiological markers for naturalistic actions following the observation of errors. It is the first time the manipulation has been used with individuals who have suffered M/S TBI. The method bridges a gap in the current body of research between laboratory tasks (with little resemblance to naturalistic actions) and tasks using naturalistic behaviors similar to those seen in day-to-day life. To explain the gap that exists between

laboratory and naturalistic types of experimental tasks and to explain how this study attempted to bridge that gap it is necessary to spend some time laying a foundation of relevant information.

In an attempt to create the necessary foundation, I will first discuss EEG measurement. Second I will discuss the neurophysiological markers used in the current study. Third I will discuss the difficulties of measuring the proposed markers in individuals with M/S TBI. Finally I will discuss the proposed method for evaluating neurophysiological markers of error processing in individuals with M/S TBI using a task more similar to naturalistic behaviors used in day to day life.

Electroencephalogram and Measurement of Event-Related Potentials

One tool with the potential to help elucidate neurological factors involved in the completion of naturalistic behaviors following M/S TBI is the electroencephalogram (EEG, Dale & Halgren, 2001; Freeman, Ahlfors, & Menon, 2009; Menon, Gati, Goodyear, Luknowsky, & Thomas, 1998). The EEG was first introduced in 1929 by Hans Berger (Gloor, 1969). It is used to detect changes in the frequency and amplitude of minute (in the microvolt range) electrical currents produced by the brain through electrodes placed on the scalp. Researchers generally agree that cortical pyramidal cells, with their long apical dendrites that run perpendicular to the scalp, are the source of the EEG signal (Kirschstein & Kohling, 2009). The vast majority of cognitive processes that take place within the cortical surface of the brain are in some way connected to the dendrites of these cells (Kirschstein & Kohling, 2009). Furthermore, because of the electrical spread of postsynaptic potentials and other charge creating biochemical mechanisms, these cells are essentially electrical dipoles. Both excitatory and inhibitory inputs generate a positive or negative charge depending on their location along the apical dendrites. Negative deflections in the EEG waveform are due to superficial excitatory or deep inhibitory

inputs. Positive deflections result from deep excitatory or superficial inhibitory activation (Kirschstein & Kohling, 2009).

The electrical potentials detected using EEG are a summation of multiple electrical fields generated throughout the brain which must pass through the meninges, cerebrospinal fluid, and the skull. These substances essentially act as low-pass filters and reduce the range of signals that reach electrodes placed on the scalp. In addition, signals oriented tangentially to the scalp or in closed fields do not reach scalp electrodes and are thus not directly detectable by the EEG (Kutas & Dale, 1997). A "closed field" is an arrangement of neurons whose electrical charges are oriented opposite to each other in such a way that they cancel each other out and thus are not detectable at the scalp. The hippocampus, with its semi-circular arrangement of cells is an example of a "closed field." (Kutas & Dale, 1997; Swick, 2005).

Despite the relative limitation of only detecting specific electrical fields, EEG is useful in the study of error processing because it allows millisecond-level temporal resolution for events taking place within the brain. Such exact resolution allows for the study of specific cognitive events and aids in revealing the temporal sequencing of these events. Whereas the analysis of EEG data can take many forms, this study will focus on the use of event-related potentials (ERPs) as a means of studying error processing in the brain.

Event-related potentials are small changes in an EEG signal which occur in response to specific internal or external events (Otten & Rugg, 2005). Generally, these small signal changes are too small to be seen in the unprocessed EEG data. Event-related potentials are extracted from the overall EEG waveform by averaging data from response-locked or stimulus-locked segments of the EEG waveform over multiple trials. For example, a participant might be asked to respond to a task by pushing a button. Each time the button is pressed the recorded EEG data

is marked. During analysis only a specific time frame around the mark is used. This process is what is known as response locking. Response locked segments are then averaged together to eliminate background noise (e.g. unrelated thoughts thought process). What remains after averaging together response locked segments of multiple trials is called an ERP (event related potential) because it is an electric scalp potential that is consistently linked with a response locked event.

Different types of ERPs are referred to as components. An ERP component can be defined in one of three ways: (1) as a maximum or minimum peak in the processed ERP waveform (highest peak at 300 ms), (2) as a specific aspect of the ERP waveform (e.g., a long slow rise), and/or (3) as a waveform that has been associated with a specific neural structure (Fabiani, Gratton, & Federmeier, 2007). In each case an ERP component is assumed to be functionally related to a specific experimental manipulation (e.g., an unexpected noise) because it co-varies with the manipulation across subjects, conditions, and scalp localization.

Study-Specific Event-Related Potentials

In this study, I focused on four specific ERP components that have been linked to manipulations involving cognitive control and could supply additional information about naturalistic error processing following M/S TBI. The four ERPs were the P300, the observer error related negativity (oERN), the observer correct trial negativity (oCRN), and the N1. The P300 and oERN were the principal focus of the two experimental tasks conducted in this study while the oCRN and N1 were used to establish group equivalence. Each of these components and their use in the current study are described below.

The P300 is a large positive-going ERP component that peaks approximately 250-500 ms after a rare task relevant stimulus (Polich, 2007). The P300 is hypothesized to reflect several

related abilities. First, it is believed to index the allocation of capacity-limited resources toward motivationally salient environmental stimuli (Duncan-Johnson & Donchin, 1977, 1982; Duncan, Barry, Connolly, Fischer, Michie, Näätänen, et al., 2009; Hajcak, MacNamara, & Olvet, 2010; Johnson & Donchin, 1980; Polich, 2007). Second, in a highly cited work Polich (2007) proposed that the P300 represents an inhibitory response which suppresses undesirable neuronal activity to allow motivationally salient information to process more quickly and with less chance for error. Finally, de Bruijn et al. (2007) suggested that the P300 may be related to error processing for more complex error-related information.

The amplitude of the P300 is influenced by multiple task-related and cognitive factors. For example, stimulus probability affects P300 amplitude, with a lower probability items eliciting a larger P300 amplitude than higher probability items (Duncan-Johnson & Donchin, 1977; Duncan, Barry, Connolly, Fischer, Michie, Naatanen, et al., 2009). Thus, if one item on a task is less probable than another item P300 amplitude will be greater for the less probable item. Salience of the task or stimulus (e.g., items with a high reward value or affective significance) is associated with increased P300 amplitude (Hajcak et al., 2010; Keil et al., 2002; Yeung & Sanfey, 2004). Further, the degree of attentional resources allocated to a task directly affects the amplitude of the P300. For example, items that would normally elicit a P300 fail to do so if attention is directed away from the item (Duncan-Johnson & Donchin, 1977; Hillyard, Hink, Schwent, & Picton, 1973). Physical features of a stimuli or factors affecting response production (e.g., responding with a hand versus a foot), are not related to P300 amplitude (Duncan, Barry, Connolly, Fischer, Michie, Naatanen, et al., 2009). The exact timing of the P300 depends on a subject's age. The timing of the P300 latency decreases with development and then increases slightly with each year of life. Increases in P300 latency are accompanied by a decrease in P300

amplitude with age (Hajcak et al., 2010; Pfefferbaum, Ford, Wenegreat, Roth, & Kopell, 1984; Walhovd, Rosquist, & Fjell, 2008). The exact significance of age-related changes on the P300 as it relates to resource allocation or error processing is not completely understood.

Several studies have reviewed the effects of TBI on the classic P300 in various tasks. Most tasks have been simple laboratory based tasks such as identifying target tones or colors (e.g., Lew, Lee, Pan, & Date, 2004) or completing a series of simple tasks with go/no go or letter identification paradigms (e.g., Duncan, Kosmidis, & Mirsky, 2003). A few studies have looked at more complex stimuli such as identification of facial expressions (e.g., Lew, Thmander, Gray, & Poole, 2007). Findings suggest that the P300 should index cognitive control mechanisms in naturalistic actions given its hypothesized role in inhibition or resource allocation. But, only one study to date has evaluated the P300 using a naturalistic action based task (de Bruijn et al., 2007) and no studies to date have used a naturalistic action based task in individuals with M/S TBI.

Evaluation of the P300 in individuals with M/S TBI requires an understanding of how the P300 varies following TBI. Findings are mixed but the general consensus is that TBI is related to a small but significant decrease in P300 amplitude and increase in P300 latency for individuals a few months after TBI compared to controls. That being said, the actual demands of the experimental task (as mentioned above) and time since injury play a role in P300 amplitude and latency. Bashore and Ridderinkhof (2002) conducted a meta-analysis of cognitive slowing and found that in general TBI increases or slows P300 latency for a few months followed by a relatively rapid return to near normal latency in less than six months post injury. Law, Cremona-Meteyard, and Geffen (1994) used a go/no go task to evaluate P300 amplitude and latency following TBI and found that as time since injury increased changes in P300 amplitude and latency approached normalcy on visual P300 tasks. Duncan, Kosmidis, and Mirsky (2003)

compared individuals with M/S TBI who were at least 2 years post injury with healthy controls on an auditory and visual P300 task. They found significant differences in P300 amplitude and latency which correlated with injury severity on an auditory task but no significant difference on visual tasks. In summary, whereas TBI does have an effect on P300 amplitude and latency, individuals demonstrate relatively rapid resolution of amplitude and latency differences on visual P300 tasks.

The second ERP component used in the current study is the observer-ERN or oERN. The oERN is a negative deflection in the ERP that peaks between approximately 150-300 ms after an error with maximum amplitudes at fronto-central regions of the scalp (de Bruijn & von Rhein, 2012; Koban, Pourtois, Vocat, & Vuilleumier, 2010). It was first identified in 2004 (Miltner, Brauer, Hecht, Trippe, & Coles, 2004; van Schie, Mars, Coles, & Bekkering, 2004). The oERN is produced when a participant views another individual commit an error. Bates Patel and Liddle (2005) demonstrated that the oERN was a unique ERP component that indexed error processing and not simply a sensory ERP such as the N2. It has been suggested that similar processes are involved in both the oERN and the more traditional error related negativity (ERN), the analog of the oERN following personally committed errors (Carp, Halenar, Quandt, Sklar, & Compton, 2009; de Bruijn et al., 2007; van Schie et al., 2004). No studies to date have attempted to elicit an oERN from individuals with M/S TBI. Elicitation of an oERN following M/S TBI would supply an additional tool for understanding action errors following M/S TBI. In order to understand the possible utility of the oERN for exploring naturalistic action errors it is necessary to first review the literature on the ERN.

The ERN is an ERP component that is prominent in fronto-medial sections of the scalp-recorded EEG and peaks approximately 50-130 ms after committing an error (Falkenstein,

Hohnsbein, Hoormann, & Banke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993). The precise mechanisms generating the ERN are still being debated (Holroyd & Coles, 2002; Yeung et al., 2004; Yeung & Cohen, 2006). Theories generally ascribe the ERN to the simultaneous activation of two competing response options (e.g., an error response and a correct response, Carter et al., 1998), error detection (Gehring et al., 1993), reinforcement learning from errors (Holroyd & Coles, 2002), or an emotional response to errors (Larson, Perlstein, Stigge-Kaufman, Kelly, & Dotson, 2006; Vidal, Hasbroucq, Grapperon, & Bonnet, 2000). In short, the ERN is an ERP which indexes the evaluate components of cognitive control and error processing. Attempts to localize the anatomical source of the ERN have pointed to the anterior cingulate cortex (ACC) as the likely generator of this ERP component (Gemba, Sasaki, & Brooks, 1986; Menon, Adleman, White, Glover, & Reiss, 2001; van Veen & Carter, 2002).

Considerable research has been compiled about the ERN. Investigations have tended to focus on factors that affect the amplitude of the ERN. For example, negative affect is a factor that increases the amplitude of the ERN (Hajcak, McDonald, & Simons, 2003; Luu, Collins, & Tucker, 2000). Trait levels of anxiety are associated with increased ERN amplitude (Hajcak et al., 2003) while individuals with depression demonstrate altered ERN amplitudes (Holmes & Pizzagalli, 2008). Motivation has a modulating effect on ERN amplitude (Gehring et al., 1993). For example, if participants are instructed to focus on speed over accuracy then ERN amplitudes are reduced (Gehring et al., 1993). If participants are then instructed to focus on accuracy over speed ERN amplitudes increase (Gehring et al., 1993). This finding is often interpreted to indicate that a participant's focus and degree of attention on accuracy directly effects ERN amplitude. (Davies, Segalowitz, & Gavin, 2004; Nieuwenhuis et al., 2002). Personality traits can also influence ERN amplitude. For example, individuals who tend to be high risk takers

have been shown to have a decreased ERN amplitude (Santesso & Segalowitz, 2009; Segalowitz & Dywan, 2009). Recent data collected by Larson and Clayson (2011) suggest a relationship between ERN amplitude and neuropsychological measures of executive functioning/cognitive control (e.g., the Trail Making Test Part B). As an index of the evaluative components of cognitive control the ERN and by extension the oERN provide a means of understanding changes in cognitive control following M/S TBI. Exploration of the ERN and in the naturalistic setting possibly the oERN (if individuals with M/S TBI can be shown to reliably produce an oERN) could supply valuable information about the integrity of the evaluative component of cognitive control following M/S TBI.

The third component that will be analyzed in this study is the oCRN. The oCRN is the correct-trial analog of the oERN and shares a similar timing and waveform morphology. The oCRN is the observer-based representation of the correct trial negativity (CRN). The waveform morphology of the CRN is similar to the ERN but the CRN has a smaller amplitude (Coles, Scheffer, & Holroyd, 2001). Few studies have targeted the CRN specifically, but the studies do offer some insights into the functions the ERP indexes. Bartholow et al. (2005) demonstrated that the CRN may index conflict between internal representations of overall response strategy to an experimental task. Allain, Carbonnell, Falkenstein, Burle, and Vidal (2004) found that the amplitude of the CRN directly before an error was smaller than directly before correct trials. They proposed that CRN amplitude may index trial-by-trial application of cognitive control with reduced control proceeding error trials. In addition, there is some evidence that suggests CRN amplitude is larger in individuals disposed to chronic worry (Hajcak et al., 2003).

In studies using between group comparisons the CRN is generally used to establish group equivalence when making comparisons on indices of error processing such as the ERN. For

example, individuals with M/S TBI, especially those with severe TBI, may have anatomical differences in the scalp, in the meninges, in tissue density, and/or in the actual electrophysiology of the brain (e.g., the balance in neuronal inhibition vs. disinhibition and/or synaptic changes) which can alter the electrical signature of the brain (Cohen et al., 2007). Thus, in isolation, any difference in ERN amplitude between control and experimental groups would allow for only weak inferences about error processing in an M/S TBI population; however, if anatomical changes could be established as an unlikely source for any observed differences than stronger inferences become possible. The CRN serves this purpose. If CRN amplitudes do not vary significantly between groups but other ERPs of interest (e.g., the ERN) do, then it supplies strong evidence that healthy controls and individuals with M/S TBI are processes non-error related information in a similar fashion. It then becomes more likely that injury related factors have not led to a generalized modification in overall electrophysiological activity but that differences in ERN amplitude are the result of error specific damage or changes unique to error processing. Thus, ERP components such as the CRN play an important role in establishing group comparability on indices of error processing. For the purpose of the current study the oCRN will be used for a similar reason. If oCRN amplitudes are consistent between groups then it lends support to the hypothesis that any oERN differences index error specific changes in cognitive control and not generalized changes in neurological functioning.

The fourth ERP component I will examine in this study is the N1. In a similar way to how the CRN is used as a measure of generalized electrophysiological change, the N1 has been used to confirm that physiological changes in early sensory perceptual processes are not directly responsible for group differences in P300 amplitude (Larson, Kelly, Stigge-Kaufman, Schmalfuss, & Perlstein, 2007). The N1 is an ERP component composed of two possible

subcomponents. The early N1, which peaks around 140 – 180 ms, and the late N1, which peaks between 180 and 220 ms after the presentation of a sensory stimulus (Kasai & Takeya, 2012; Makeig et al., 1999). Both components are associated with attentional processing of sensory stimuli particularly the visual experiencing of objects (Kasai & Takeya, 2012; Muñoz-Ruata, Caro-Martínez, Martínez Pérez, & Borja, 2010; Rosburg, Boutros, & Ford, 2008).

Traumatic Brain Injury and Event-Related Potential Measurement

The use of ERPs in the study of traumatic brain injury has been well established (e.g., Knight, 1984; Larson & Perlstein, 2009; Potter, Basset, Jory, & Barret, 2001). However, TBI tends to complicate the interpretation of ERP data. For example, physical changes in the brain, scalp, and skull, can alter the conductive properties of these mediums thereby changing scalp recorded electrical signals (Swick, 2005). In addition, latency, or the time to peak of an ERP component, is often longer in individuals with TBI relative to controls (Lachapelle, Bolduc-Teasdale, Ptito, & McKerral, 2008). The exact neurological mechanism leading to differences in latency are not completely understood at this time; however, in a meta-analytic review of the literature Bashore and Ridderinkhof (2002) evaluated evidence for various explanations for latency shifts including metabolic changes, neuronal changes, process specific deficits and generalized slowing. The one undisputed finding was that M/S TBI produced clear generalized slowing, which affects response times and other cognitive processes. Nevertheless, Bashore and Ridderinkhof also found considerable variability among individuals with TBI in the degree of slowing. Variability in the amount of slowing in M/S TBI populations can be problematic in the analysis of ERPs especially if it produces variations in component latency.

Inconsistency in the time to the peak of an ERP component is called latency jitter. It is problematic in ERP analysis because it can create artificial differences in amplitude. These

differences in amplitude result from the process of averaging response locked EEG waveforms to eliminate noise. Individual trials are combined together to create an average waveform for each participant. These individual participant waveforms are then averaged together to create a grand average waveform for the group. As the variance in peak latency increases, the amplitude of the grand mean decreases. The result is a long flat plateau instead of a tall short peak that is due to the imprecision (i.e., jitter) in the latency of the peak.

Latency jitter can affect the selection of the correct waveform component. For example, the ERN generally appears between 50-130 ms after the commission of an error. This time frame may shift for some but not all individuals with TBI. As a result, when the waveform is extracted peak amplitudes of some but not all of the trials will be beyond the extraction time window and the computer algorithm used to select a peak will select a point which does not represent the true ERN peak. Errors in peak selection introduce error into estimation of amplitude. The increased error can be accommodated to a degree by slightly increasing the window of interest and using area based measurements such as the mean to reduce noise and produce acceptable reliability in ERP measurement (Clayson, Baldwin, & Larson, 2013). It must always be remembered though, that in populations with increased latency jitter spurious relationships based on statistical artifact as opposed to real life changes in amplitude can be produced. Latency jitter is simply a known weakness in the interpretation of ERP amplitudes.

Latency jitter is also problematic for the interpretation of between group differences on ERP latency. Latency jitter theoretically increases within group variability and limits the identification of between group differences using statistical analyses. One technique that can be used to limit the effect of latency jitter when comparing groups is the use of an area based measure of latency such as centroid latency (Dien, Spencer, & Donchin, 2004; Luck, 2005).

Centroid latency is a measure of central tendency which finds the center of "mass" or central point of the area under a curve. In other words the area of latency variability is calculated between the minimum and the maxim latency value of the sample. A central point is then calculated for the area encompassed by the sample as the point of centroid latency (Dien et al., 2004). Clayson, Baldwin, and Larson (2013) found that centroid latency, while consistently more biased than mean latency estimates, was more efficient at categorizing a group tendency or reducing noise in within group variability on measures of latency. Clayson, Baldwin, and Larson used the example of shooting a rife at an imaginary target with the bull's-eye representing the true component latency as a means of explaining bias and efficiency. In this case centroid latency was consistently off target (biased) but created tight groups of shots (efficiency), while the commonly used peak latency value was closer to the target (less biased) but was scattered all around the target in a wide pattern (less efficient). As a result, Clayson, Baldwin, and Larson agreed with Luck (2005) in stating that centroid latency was the measure of choice when making between group comparisons using ERP latency. That being said, centroid latency does not completely eliminate the effects of latency jitter and it is only appropriate for ERP components with more lengthy waveforms (Luck, 2005).

Perhaps as a result of the complications introduced by TBI, few studies have looked at error processing in TBI using ERPs. For example, a study by Larson, Kaufman, Schmalfuss, and Perlstein (2007) was the first study ever published using the ERN to evaluate changes in error processing following M/S TBI. The authors found significantly reduced ERN amplitude but no significant difference in CRN amplitude in individuals with TBI as opposed to healthy controls on a simple color-naming Stroop task. An equivalent CRN was particularly important in these findings. Equivalent CRN amplitude supplied the authors with strong evidence that differences

in ERN amplitude were not simply the result of anatomical changes, latency effects, or overall bad brain. Their results suggested error specific changes in the activation of error related neuronal structures for individuals with M/S TBI. Several studies have evaluated the P300 following M/S TBI. For example Lew, Thomander, Gray, and Poole (2007) evaluated the P300 in individuals with severe TBI on four experimental tasks, two auditory and two visual. Lew et al. wanted to see if complex tasks discriminated controls and individuals with severe TBI better or with more accuracy than simple tasks. The tasks included in the experiment were a simple tone based auditory discrimination task, a simple color discrimination task, a word discrimination task, and an emotion discrimination task using facial expressions. Lew et al. specifically chose the word and facial expression tasks as they felt the tasks were more ecologically relevant than the tone and color discrimination tasks commonly used in the study of the P300. They hoped to evaluate the clinical utility of the P300 in making predictions following M/S TBI. Lew et al. hypothesized that the more complex tasks would require greater cerebral resources and proposed that they would better discriminate individuals with TBI from healthy controls. Contrary to their hypothesis they found that the simple tasks better differentiated groups.

There are two important points illustrated by Lew et al.'s research which I wish to reiterate. One, as expounded by Lew et al. (2007) the simple experimental tasks used in the vast majority of ERP studies have little ecological validity. Two, there is currently little or no empirical evidence on how to make generalizations from such studies to more ecologically valid naturalistic behaviors seen in daily life. Lew et al. also demonstrated that making predictions about ecologically relevant tasks using ERP data from less complex tasks is not always straightforward. As the body of research currently stands there is a large gap between

empirically supported theories of cognitive control and error processing and application of that knowledge in clinically relevant ways. Expansion of the large body of ERP research into a clinically useful database requires that researchers begin the process of creating a bridge. The bridge would need to connect neurophysiological markers detected and defined using tones, colors, and arrows to applications that can be used in understanding normal and abnormal naturalistic behaviors.

Observation and Event-Related Potentials: A Way to Bridge the Gap

Applying ERPs to the study of naturalistic independent goal directed activities like those found in daily living has proven problematic. As stated above, experimental tasks designed to investigate ERPs generally have little resemblance to everyday tasks. Tasks designed specifically to evaluate naturalistic goal directed activities are impracticable for EEG because they require considerable movement. Movement related electrophysiological noise makes isolation of specific cognitive events and ERP components virtually impossible. As a result, little research has been done to link the findings obtained using laboratory based tasks with those involving more naturalistic behaviors. Linking the two bodies of research requires finding a way to reduce the effects of movement on ERP recording and analysis.

Fortunately, the findings of Miltner, Brauer, Hecht, Trippe, and Coles (2004) demonstrated one way to reduce the effects of movement on ERP recording and bridge the gap between tasks using behavioral observation. Miltner et al. demonstrated that observation of errors committed by others was sufficient to elicit error-related ERPs. Other studies have confirmed that observation of another's error is sufficient to produce a variety of error related ERPs including the P300, oERN, and oCRN (Carp et al., 2009; de Bruijn et al., 2007; Koban et al., 2010).

With this in mind, One way of bridging the gap between laboratory based tasks and naturalistic action type tasks is for subjects to calmly sit and observe others engaging in naturalistic actions. Observation of another's errors would eliminate the need for movement. A recent study by de Bruijn, Schubotz, and Ullsperger (2007) used a picture based manipulation to explore error processing for more naturalistic errors in a group of healthy college students. The task required subjects to observe a rapid sequence of pictures depicting simple naturalistic actions such as pouring water into a glass or cutting out shapes on a paper. Participants were shown one of two conditions: a correct condition where the person in the picture conducted the task correctly, or an incorrect condition where the person in the picture spilled the water or cut the shape in half instead of cutting along the edge. de Bruijn et al. found a significantly increased P300 amplitude between error and correct trials, which was somewhat unexpected. In order to explain his findings the authors postulated a second cognitive control process related to higher level executive functions which may become active only when more complex error situations are evaluated.

In the current study I hoped to build off the work of de Bruijn et al. (2007) and Miltner et al. (2004) by using observation based ERPs to gain additional insight into the effects of M/S TBI on error processing both on laboratory and naturalistic action tasks. During the study I evaluated the hypotheses that individuals with M/S TBI would produce sufficiently large ERPs to allow for group comparisons in both laboratory and naturalistic based tasks and that group differences on ERPs would correlate with behavioral changes following M/S TBI. The study attempted to bridge the gap between the two bodies of experimental literature (the laboratory-based ERP literature and the more naturalistic-action based behavioral literature) and expand our understanding of error-related impairments following M/S TBI.

Specific Aims and Hypotheses

I used error related ERPs in two separate tasks as a means of gaining additional insight into why individuals with M/S TBI commit more errors, correct less errors, and have reduced insight into error behaviors than healthy controls. I compared participants with M/S TBI and healthy controls on two tasks: (1) A modified version of the picture task presented by de Bruijn, Schubotz, and Ullsperger (2007) meant to evaluate naturalistic error processing in TBI, and (2) on a standard error observation task as a proof of concept that the oERN can be reliably elicited and used to studying observed errors following M/S TBI. The specific aims of this dissertation are, therefore, as follows:

Aim 1: *To determine if individuals with TBI would produce measureable observer-based ERP components.* Specifically I examined whether individuals who experienced a M/S TBI would produce an oERN and P300 in response to observing the errors of others.

Hypothesis: I hypothesized that individuals with M/S TBI would produce measurable observer based ERP components on a laboratory based observer task and on a more naturalistic error based task.

Aim 2: *To determine if TBI modified an individual's error-related neurophysiologic reaction to observation of errors on a standard error task compared to controls.* Specifically, I examined the effects of M/S TBI on the amplitude of the oERN and oCRN as a reflection of cognitive control processes related to error detection and awareness.

Hypothesis: I hypothesized that individuals with TBI would demonstrate an error-specific reduction in neurophysiologic reaction to observed errors when compared with demographically-similar healthy controls. Reduced neurophysiologic

reaction would consist of a reduction in the amplitude of the oERN with stable oCRN amplitude between healthy controls and individuals with M/S TBI.

Aim 3: *To evaluate if M/S TBI modified an individual's error-related ERP reaction to observed naturalistic errors when compared to healthy controls.* Specifically, I examined the effects of M/S TBI on the amplitude of the P300 as a reflection of cognitive control processes related to error detection and awareness.

Hypothesis: Participants with M/S TBI would demonstrate an error-specific reduction in neurophysiologic reaction to observed naturalist errors compared with healthy controls. The reduced reaction would be seen as a reduction in the amplitude of the P300 with stable N1 amplitude in participants with M/S TBI compared to healthy controls. Stable N1 amplitude would lend support to the conclusion that results were not best explained by generalized physiological changes but by error specific changes.

General Procedures Common to Both Experiments

Method

Power Analysis. Because no known studies had examined group differences on ERPs using observation of naturalistic errors, I felt it important to estimate a required group size to achieve adequate power using projected effect sizes. Using the analyzed dataset to conduct post-hoc power calculations is typically thought to be inappropriate (e.g., Hoenig & Heisey, 2001). Thus, I used data from two previous studies to conduct a power analysis. As noted above, de Bruijn, Schubotz, and Ullsperger (2007) used a picture task in healthy controls to examine accuracy effects on the P300 and found a significant mean difference of 8.60 μV between error-trial and correct-trial pictures (Cohen's - *d* effect size = 0.80). In another study healthy controls

and individuals with severe TBI were compared by Larson et al. (2007) on error and correct trials using a more traditional Stroop task. They found a statistically significant Group x Accuracy interaction ($\eta^2_p = 0.26$). As the interaction effect between groups was the more similar of the two effect sizes (partial eta-squared presented above) to the current study, I then calculated an effect size *F* from the partial eta-squared to estimate the needed sample size to achieve adequate statistical power for the ANOVA analyses proposed in the current study ($F = 0.59$). Using the effect size *F* from the Larson et al. study, power of .95, an alpha level of 0.05, and a correlation of .22 between error- and correct-trial ERPs (correlation was the *r* between the ERP amplitudes for error and correct trials from the Larson et al. study), my estimated sample size calculated using G-Power software was a total sample of 18 (9 per group) for the Group x Accuracy ANOVAs presented below. Had I used the de Bruijn et al. (2007) effect size of $d = 0.8$ ($F = 0.4$) then the estimated number of participants would have been a total of 22 (11 per group). Regardless, the total sample for both experiments presented below exceeded the sample size estimates to have adequate power to detect effects based on these calculations.

Participants. I recruited 20 neurologically- and psychologically-healthy adults as a control sample and 19 survivors of M/S TBI (39 total individuals) to participate in the study. A larger sample size than estimated by the power analysis for each group was recruited to accommodate possible participant loss. Current evidence indicates that in order to produce data that is acceptably reliable and accurate participants must produce at least six usable trials for the ERN/CRN (Olvet & Hajcak, 2009), although 14 or more trials is preferred (Larson, Baldwin, Good, & Fair, 2010). Twenty usable trials are needed for a stable and reliable P300 (Cohen & Polich, 1997).

All participants were between the ages of 18-54 years. Exclusion criteria for the control group included: psychiatric diagnosis, reported alcohol or substance abuse within the past year, current antiepileptic medication use, reported history of learning disability, loss of consciousness, neurological disorder (e.g., traumatic brain injury, seizure disorder, stroke), and attention deficit hyperactivity disorder. Exclusion criteria for the TBI group included: a history of major psychopathology within two years pre-injury, reported alcohol or substance abuse within the past year, reported history of learning disability, brain disorders (e.g., epilepsy, stroke) in addition to TBI, current antiepileptic medication use, or involvement in litigation. Participants were screened for psychiatric disorders using the Mental Health Screening Form-III (MHSF-III; Carroll & McGinley, 2000, 2001).

Individuals with M/S TBI were enrolled in the study only if they were at least six months post-injury in an attempt to provide some degree of control with respect to time-since-injury and in an attempt to use only participants experiencing relatively "stable cognitive sequelae" (Rao & Lyketsos, 2000). That is, I wanted to utilize participants who were out of the period of spontaneous recovery from their injury. Mean time since injury in the M/S TBI group was 115.32 (*SD* = 95.10) months with a range of 39 – 388 months. All participants were medically stable and capable of providing their own written informed consent. Individuals with TBI were asked to bring copies of their medical records for the purpose of severity classification. If the participants did not have copies of medical records TBI participants were asked to complete a signed consent form giving the primary investigator permission to request TBI related medical records from their health care providers. I was able to obtain medical records from 11 participants (see Table 1). For those whom I could not get medical records I verified injury characteristics with their physician (*n* = 3) and/or injury accounts with family members (*n* = 5).

Severity classification was determined using the following markers: duration of loss of consciousness (LOC), duration of post-traumatic amnesia (PTA), and lowest Glasgow Coma Scale (GCS) score (Teasdale & Jennett, 1974). Moderate TBI was defined as follows: lowest-point GCS score between 9 and 12, LOC between 30 minutes and 6 hours, or PTA between 1 and 7 days. Severe TBI was defined as having a lowest recorded GCS score less than 9, LOC greater than 6 hours, or PTA greater than 7 days (Hannay, Howieson, Loring, Fisher, & Lezak, 2004; Lucas & Addeo, 2006). If severity criteria were not consistent (e.g., LOC in the severe range with GCS in the moderate range) then duration of PTA was used to define TBI severity. Table 1 contains a summary of medical record information, demographic characteristics, and group assignment for all participants with M/S TBI. The participant sample consisted of 9 individuals who sustained their injuries in motor vehicle accidents, 5 from falls, 2 from bicycle accidents, 1 from an all-terrain vehicle accident, 1 from an assault with a baseball bat, and 1 from a horse kick. Each participant completed one study session containing three main components: (1) the administration of questionnaires, (2) administration of neuropsychological tests, and (3) the recording of event-related potentials (ERPs) during two separate computerized tasks.

Questionnaires. Participants were asked to complete two self-report measures: (1) a measure of depression and anxiety used to evaluate group differences in negative affect which could affect ERN amplitudes; and (2) a measure of executive functioning used to connect ERP findings to self-reported functional deficits.

Table 1

Description of TBI Participant Injury Characteristics and Injury Verification

Age	Sex	Etiology	LOC Hours	PTA Hours	Months Post	Observer Group	Picture Group	Medical Record	Physician Verified	Patient Account
20	M	MVA	288	288	18			X		
28	M	FALL	0	96	132	X	X	X		
26	M	MVA	0.5	72	57	X	X	X		
40	F	BICYCLE	*	8	51			X		
30	M	FALL	1	*	352	X	X	X		
22	M	MVA	384	1440	39	X	X	X		
21	M	ATV	504	840	84	X		X		
46	M	MVA	336	672	100	X	X		X	
51	M	FALL	288	1080	63	X	X		X	
26	F	HORSE	504	720	76		X		X	
48	F	MVA	1800	2136	64	X	X	X		
37	F	MVA	24	24	202	X	X	X		
49	M	BICYCLE	*	24	79	X	X	X		
31	M	ASSAULT	192	1512	133	X	X	X		
23	F	MVA	0	168	70	X	X	X		
19	F	FALL	0.75	48	80	X				X
51	M	FALL	120	336	89	X	X			X
45	M	MVA	0.25	48	388	X	X			X
43	F	MVA	1.5	576	37	X	X			X
		Mean:	261.41	560.44	111.26					
		SD:	424.57	609.49	97.49					

MVA = Motor Vehicle Accident, ATV = Three Wheeled All-terrain Vehicle Accident, X = Included in Group

*Unknown because of time and circumstances of injury

Hospital Anxiety and Depression Scale (HADS). The HADS is a 14-item self-report measure designed to assess anxiety and depression in populations with pronounced physical symptoms unrelated to psychological phenomena such as in individuals with M/S TBI. The HADS shows high reliability with a Cronbach's alpha of .83, and good concurrent validity with the Beck Depression Inventory(r = 0.62 to 0.73) and the Symptom Checklist – 90 (SCL-90; 0.67 to 0.76) two gold standard measures of depression and anxiety (Bjelland, Dahl, Haug, & Neckelmann, 2002). Studies have evaluated the usefulness of the HADS specifically following TBI including evaluation of its factorial model (Schönberger & Ponsford, 2010) and concurrent validity (Whelan-Goodinson, Ponsford, & Schönberger, 2009). In each instance the HADS was found to be a valid measure of emotional distress following TBI.

Frontal Systems Behavior Scale – Self Rating Form (FrSBe). The FrSBe is a 46-item measure of cognitive and behavioral change used for evaluation of post injury functioning following TBI. Primary data reporting includes overall composite score and three subscales (apathy, disinhibition, and executive functioning). The measure has both a participant (self-report) and significant other form and can be used to compare pre-injury and post injury functioning. The FrSBe shows adequate reliability (internal consistency 0.96; split half 0.93) and validity (Grace & Malloy, 2001).

Neuropsychological Tasks. Participants also completed the following neuropsychological tests to summarize levels of cognitive functioning in areas related to error processing. The purpose of the neuropsychological measures was to provide additional explanatory information for understanding between group differences on ERPs.

North American Adult Reading Test (NAART). The NAART is frequently used as a measure of premorbid intellectual functioning following a brain injury or cognitive status change

such as dementia (Spreen & Strauss, 1991). It serves as a good estimate of Wechsler Adult Intelligence Scale-Revised (WAIS-R) and the Wechsler Adult Intelligence Scale-III (WAIS-III) composite scores, especially in the average range of ability (Johnstone, Callahan, Kapila, & Bouman, 1996). The NAART has good reliability with a Cronbach's alpha of .93 (Uttl, 2002) However, the NAART tends to overestimate low IQ scores and underestimate high IQ scores (Johnstone et al., 1996).

*Digit Span Forward and Backward***.** In the digit span forward test of the WAIS-III, increasingly longer strings of numbers are recalled (2-9 numbers). In the backward version, participants repeat the numbers in reverse order. Span length is defined as the number of digits recalled correctly before two strings of the same length are failed. Reliability estimates of Digit Span range from 0.84 to 0.93 and its correlation with the working memory index of the WAIS-III was estimated at 0.83 in a normative sample (*WAIS-III and WMS-III Technical Manual*, 1997).

Trail Making Test (TMT) Parts A and B. The Trail Making Test (TMT) Parts A & B are well-documented measures of visual scanning, processing speed, and task switching (Lezak, 1995). The TMT consists of two parts. During Part A, participants connect numbered circles in consecutive order, while in Part B, participants connect numbered and lettered circles in order and must alternate between the two sequences. Psychometric studies indicate and adequate test re-test reliability coefficient for Part A at 0.79 and a high coefficient for Part B at 0.89 (Strauss, Sherman, & Spreen, 2006). Several studies indicate that the two Trail Making Tests are sensitive to the global effects of brain injury (Botwinick, Storandt, Berg, & Boland, 1988; Buchanan, Strauss, Kirkpatrick, Breier, & Carpenter, 1994), and Trails B is reported to be specifically sensitive to prefrontal dysfunction because of the requirement to shift sets (Butters, Kaszniak, Glisky, Eslinger, & Schachter, 1994).

Controlled Oral Word Association Test (COWA) and Animal Naming. In the COWA, participants are asked to produce as many phonemically related words as possible that begin with the letters “F”, "A”, and “S.” Similarly, on the animal naming or category fluency test participants are asked to name as many animals as possible in a one minute (Benton, 1994; Gladsjo et al., 1999). The test has high reliability with a Cronbach’s alpha of .82 and a test-retest reliability of r = .74 (Ruff, Light, Parker, & Levin, 1996).

Rey Auditory Verbal Learning Test (RAVLT). The RAVLT is a brief assessment of new learning, immediate memory, delayed memory, and recognition memory. The measure consists of a list of 15 nouns. During the learning phase the list is read aloud to the participant repeatedly over five learning trials and after each learning trial the participant is asked to recall as many words as possible and repeat them back to the examiner. Following a brief distractor list the participant is asked to again remember as many words a possible from the original list of 15 words as part of the immediate memory phase of the RAVLT. During the delayed memory phase the participant is asked to repeat the 15 word list after a 30 minute delay. The participant is then asked to identify each of the 15 words from the original list out of a list of distractor words for a recognition phase of the test. The RAVLT has a test retest reliability of r = .60 to .70 and strong construct validity (Rey, 1958).

Computerized Tasks. Presentation of the computerized tasks was counterbalanced with half of the participants receiving the observer task first. Computerized tasks were designed based on previous tasks reported in the literature which reliably produced the ERPs under investigation including the ERN, P300, CRN, and N1. Tasks were constructed specifically to evaluate the ERPs in the context of cognitive control and error processing. During the tasks, participants sat in a darkened room in a comfortable chair with an EEG sensor net in place.

Stimuli were centered on a 17" computer monitor approximately 20 inches from the participant's head. Each task is described individually below.

Electroencephalogram Data Acquisition and Reduction. Electroencephalogram data for both tasks was recorded from 128 scalp sites using a geodesic sensor net and Electrical Geodesics, Inc., (EGI; Eugene, Oregon) amplifier system (20K gain, nominal bandpass =.10-100Hz). Electrodes were used to record vertical and horizontal eye movements reflecting electro-occulographic (EOG) activity for eventual filtering. The reference electrode for EEG recording was Cz and data was digitized continuously at 250Hz with a 16-bit analog-to-digital converter. Data was digitally re-referenced off-line to an average reference. A right posterior electrode approximately two inches behind the right mastoid served as a common ground. Electrode impedance was maintained below 50kΩ and verified between tasks.

Electroencephalogram data were segmented off-line and single trial epochs rejected if voltages exceeded 100μV, transitional (sample-to-sample) thresholds were greater than 100μV, or eye-channel amplitudes were above 70μV. Data was filtered using a 30 Hz lowpass filter and a 0.1 Hz highpass filter. Eye blinks were removed from the segmented waveforms using independent components analysis (ICA) in the ERP PCA Toolkit (Pfefferbaum et al., 2000) that uses EEGLAB (Delorme & Makeig, 2004). The ICA components that correlated at 0.9 with the scalp topography of two blink templates, one generated based on the current data and another provided by the ERP PCA Toolkit author, were removed from the data (Dien, Michelson, & Franklin, 2010).

Component amplitudes were extracted as an adaptive mean for all ERPs used in the study. Adaptive means are considered the more appropriate measure of waveform amplitude in samples, such as individuals with TBI, where latency jitter and/or increased noise are expected

(Clayson et al., 2013). Calculating the adaptive mean is relatively simple and is the average amplitude of 15ms pre- to 15ms post-peak amplitude. For example, on the oERN a computerized search was used to identify the most negative point (called the peak) in each participant's individual waveform between 150 and 300 milliseconds. The window of time was defined based on previous research of general timeframes for the oERN and a review of the specific waveforms for this study. After identifying the most negative point within the time window a computer averaged the data for 15ms before and 15ms after the negative peak creating a single mean amplitude. Each of these individual subject averages was then compiled to form the group average.

Electrode locations included in the analyses were selected based on previous findings about the focal locations of the various ERPs as well as visual inspection of the scalp distributions of the present data (see Figure 1). Maximum amplitude for the oERN is typically found at cento-medial electrode sites (de Bruijn & von Rhein, 2012; Koban et al., 2010; van Schie et al., 2004) . In the current study (collapsed across groups) the oERN/oCRN adaptive mean had a maximum (i.e., most negative) amplitude at fronto-central electrodes for correct trials (Fz: M = -1.90μV, FCz: M = -2.50 μV, and Cz: M = -1.20 μV) and frontal electrodes for error trials ((Fz: M = -2.22 μV, FCz: M = -1.73 μV, and Cz: M = -0.93 μV). The oERN and oCRN were thus determined as the average activity from electrode sites 5, 6 (FCz), 11(Fz), and 12 in the time window of 150 – 300 milliseconds (van Schie et al., 2004). Averaging across multiple electrode sites is a method for reducing signal to noise ratio and increasing signal reliability in ERP analysis (Larson et al., 2010).

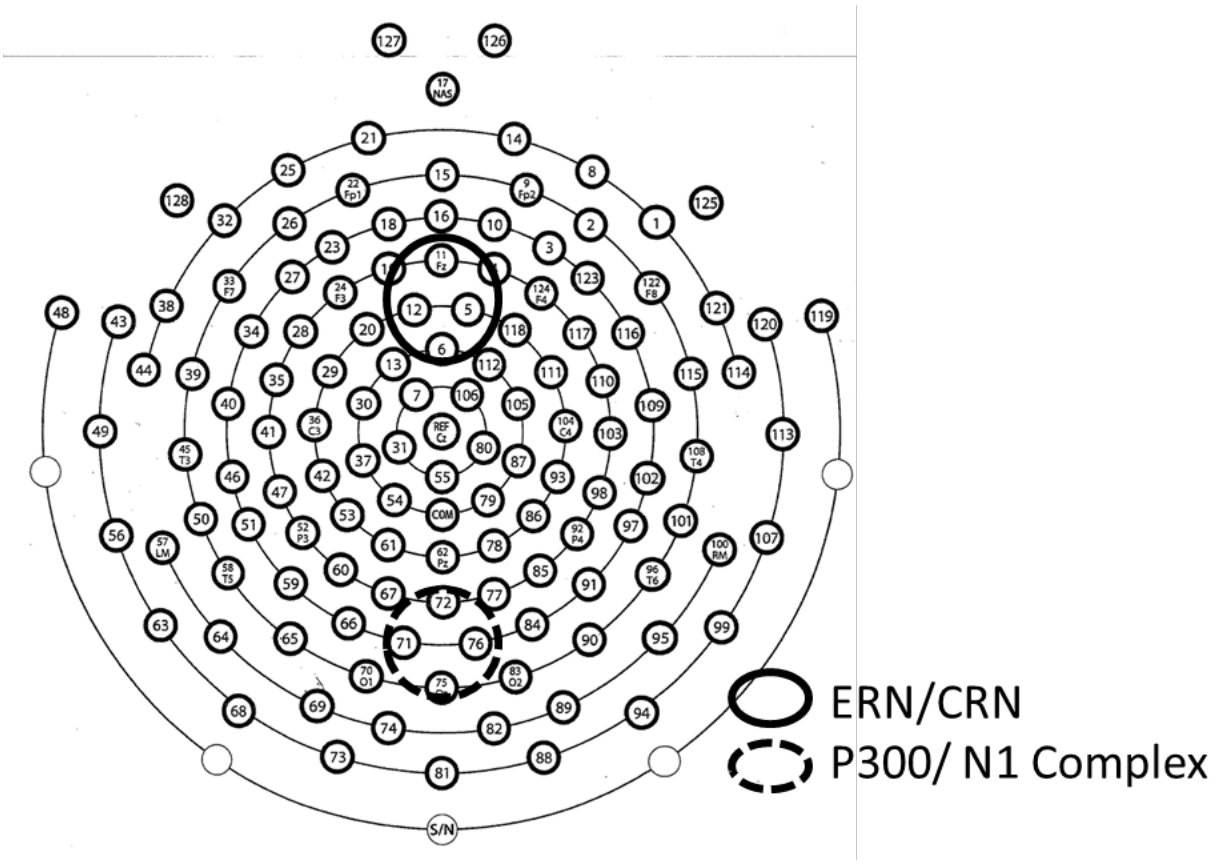

Figure 1. ERP Component Electrode Locations.

For the P300 maximum amplitude is generally measured along medial electrode sites (Duncan, Barry, Connolly, Fischer, Michie, Näätänen, et al., 2009; Polich, 2007). Adaptive mean amplitude (again collapsed across groups) was highest at Oz for the P300 on both correct (Cz: 2.85 μV, Pz: 5.11 μV, Oz: 8.63) and error trials (Cz: *M* = 3.68 μV, Pz: *M* = 5.66 μV, Oz: *M* = 8.37). The amplitude of the P300 was determined as the average activity from electrode sites 71, 72, 75 (Oz), and 76 during the time window of 250 to 600 milliseconds. The N1 maximum amplitude is generally found at parietal and occipital electrode sites (Luck, 2005). In this study I used electrodes 71, 72, 75(Oz), and 76 and the time frame of 150 – 200 ms to evaluate the N1.

Component latency for the P300 was calculated using the centroid technique as centroid latency measures represent group differences more efficiently in cases where significant latency jitter is expected (Clayson et al., 2013; Luck, 2005). Peak latency was used to calculate the latency for the oERN/oCRN and N1 as suggested by Luck (2005). Luck recommended that the statistical properties of centroid latency were most appropriate for late ERP components with longer durations such as the P300 as opposed to early ERP components with shorter durations such as the oERN and N1. He stated that centroid latency times can become very distorted if additional ERP components co-occur in the latency range of interest. Luck suggested that centroid latency be reserved for large late ERP components such as the P300 or the N400.

Statistical Analyses. Statistical analyses were conducted using the software package SPSS 20. Means and standard deviations were calculated for ERP amplitude, latency, neuropsychological measures, questionnaire data, and demographic variables. Zero-order correlations and independent-samples *t*-tests were used to evaluate the relationship between these variables and ERP amplitude or latency and to compare groups on ERPs, questionnaires, and neuropsychological measures. Significance for all analyses was set at the $p = 0.05$ level. Given the exploratory nature of the current study it was deemed more problematic to commit a Type 2 error than a Type 1 error, hence family-wise error was not corrected by reducing the *p*-value or using an accepted correction such as the Bonferroni or Tukey HSD corrections.

The studies hypotheses were: (1) That individuals with M/S TBI would reliably produce error-related ERPs during the observation of errors; (2) That individuals with M/S TBI would show reduced error-related neurophysiologic reaction to error observation on a standard error task compared to controls; and (3) Individuals with M/S TBI would demonstrate a reduced neurophysiologic reaction to observed naturalistic errors when compared with healthy controls.

Aim 1 and Aim 2 were analyzed using two separate analyses, one for the oERN/oCRN amplitude and one for component latency. Each ERP was analyzed using separate 2-Group x 2-Accuracy repeated measures ANOVA to examine Group (TBI vs. Control) x Accuracy (Error vs. Correct) effects on ERP amplitudes and latency. In these analyses, accuracy was a within-subjects variable, and group was a between-subjects variable. Aim 3 was analyzed in a similar fashion. A 2-Group x 2-Accuracy repeated measures ANOVA was used to examine Group (TBI vs. Control) x Accuracy (Error vs. Correct) effects on P300 amplitude and latency. Interaction effects for Aim 3 were decomposed using paired samples *t* –tests to evaluate differences across accuracy for each group. Between-group effects for correct and error trials were evaluated using a one-way ANOVA on both ERP amplitudes and latency.

Specific Information for Experiment 1: The Observer Task

Method

Participants. Three participants were dropped from the TBI group due to insufficient numbers of error trials remaining for ERP analysis after artifact correction and rejection (total errors 2, 0, and 0). Four individuals were dropped from the control group; one was dropped for insufficient error trials (total errors = 1) and three for failing to complete electronic surveys correctly. The final sample for experiment one, therefore, consisted of 32 individuals (12 female)—including 16 individuals with M/S TBI and 16 control participants. A summary of demographic information for the observer task in experiment one, including between-group comparisons, is presented in Table 2.

Computerized Task. The observer task was used to evaluate oERN and oCRN amplitudes between controls and individuals with M/S TBI, as discussed in specific aims one and two. During the task participants sat behind and slightly to the left of a trained confederate

who used a button pad to respond to a modified version of the Eriksen Flanker task (see Figure 2). with their left index finger if the middle arrow of a group of five arrows pointed to the left, and with their right index finger if the arrow pointed to the right.

Table 2

Demographics: Mean, Standard Deviation, and Range for the Observer Task

	Control Group			TBI Group				
	Mean	(SD)	Range	Mean	(SD)	Range	*F*	*p*
Age	32.25	(10.07)	19 - 47	35.63	(11.82)	19 – 51	0.76	0.39
Education	15.38	(2.53)	13 - 18	15.38	(2.53)	11 – 22	0.18	0.68
Estimated IQ	107.57	(7.92)	84 - 122	107.22	(6.88)	90 – 120	0.02	0.90
Sex	9 Male		7 Female	11 Male		5 Female	$\chi^2 = 0.53$	0.47

Estimated IQ = NAART Estimated Full Scale IQ

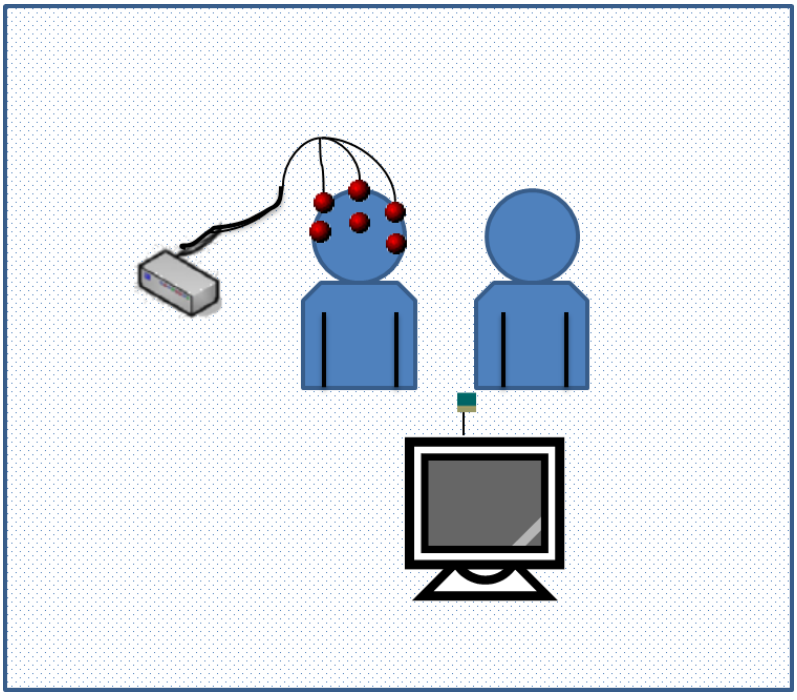

Figure 2. Experimental Design Diagram for Observer Task.

Congruent (e.g., <<<<<) and incongruent (e.g., << > <<) stimuli were shown centered on the screen. Participants observed while a confederate was presented with four flanker arrows (e.g., << <<). The target arrow was then presented in the middle of the flanker arrows after a delay of 80ms. Following participant response, a black screen was presented for 500ms to avoid interruption in neurological processing of each trial followed by a fixation mark for 500ms before beginning the next trial. Forty-five percent of the trials were congruent and 55 percent were incongruent. Congruent and incongruent trials were randomly presented. The task contained approximately 480 trials with the research confederate instructed to produce a total of 20-30 percent errors during the task. Confederates produced a mean of 103.19 (*SD* 34.11, Range 57 - 177) error trials and 376.81(*SD* 34.11, Range 303 - 423) correct trials creating an average of 27% errors on the task. Groups did not significantly differ on the number of correct trials or total trials included in each subject's ERP average waveform; however, groups did differ on the number of error trials included (see Table 3).

Results

Table 3

Observer Task Behavioral Data

	Control Group			TBI Group				
	Mean	(SD)	Range	Mean	(SD)	Range	*F*	*p*
Correct Trials	322.25	(62.38)	168-406	294.00	(94.81)	20-399	1.02	0.32
Error Trials	55.56	(24.14)	14-84	84.50	(26.06)	45-155	10.32	0.003*
Total Trials	377.81	(74.58)	191-461	378.50	(136.16)	79-474	0.00	0.98

*p = A significant p-value between groups on a 2-tailed independent samples *t* – test

Self-Report Measures. Groups significantly differed on measures of anxiety but not on measures of depression (Table 4). Differences on post-injury self-report of behavioral and cognitive functioning (FrSBe) indicated significant differences between controls and individuals with M/S TBI on the FrsBe scales of apathy, executive functioning, and the total score.

Table 4

Descriptive Statistics for Self Report Measures on the Observer Task

		Control Group			TBI Group				
		Mean	(SD)	Range	Mean	(SD)	Range	*F*	*p*
FrSBe	Apathy	26.81	(4.04)	21-34	35.00	(10.63)	20-56	8.29	0.007*
	Disinhibition	26.13	(5.76)	18-37	30.06	(9.50)	18-56	2.01	0.17
	Executive	32.38	(7.60)	19-45	42.43	(12.85)	23-76	7.27	0.01*
	Total Score	85.31	(15.20)	59-113	107.5	(31.40)	65-188	6.47	0.02*
HADS	Depression	5.69	(3.11)	1-10	7.94	(3.64)	3-15	3.53	0.07
	Anxiety	2.19	(2.20)	0-8	6.81	(5.19)	0-16	10.77	0.003*

HADS = Hospital Anxiety and Depression Scale, FrSBe = Frontal Systems Behaviors Scale

*p = A significant p-value between groups on a one way ANOVA

Aims 1 and 2: oERN/oCRN. Grand average waveforms and voltage maps for correct and error response-locked trials reflecting the fronto-medial oERN are shown below (see Figures 3 and 4). As expected, response-locked ERPs averaged across frontal electrode sites (collapsed across groups) showed a negative deflection that peaked at approximately 190.78 ms (*SD* 57.95, Range 100 – 248) for correct trials and 181.13 ms (*SD* 55.81, Range 100 – 248) for error trials. A 2 (Group) x 2 (Accuracy) repeated measures ANOVA revealed that there was no significant main effect of accuracy, $F(1,30) = 0.89$, $p = 0.35$, $\eta^2_p = 0.03$, indicating that participants did not produce a statistically-reliable oERN that differentiated correct and error trials. There was also

no significant main effect of group, $F(1,30) = .21$, $p = 0.21$, $\eta^2_p = 0.007$, and no significant Group x Accuracy interaction, $F(1,30) = 0.53$, $p = .47$, $\eta^2_p = 0.02$.

An exploratory analysis to evaluate whether the observer task produced a reliable oERN in the control sample alone was conducted given the lack of significant findings above. A univariate repeated measures ANOVA was used to evaluate control participants on accuracy. There was no main effect of accuracy on waveform amplitude, $F(1, 15) = 0.39$, $p = 0.54$, $\eta^2_p = 0.03$ suggesting that the task did not reliably produce an oERN.

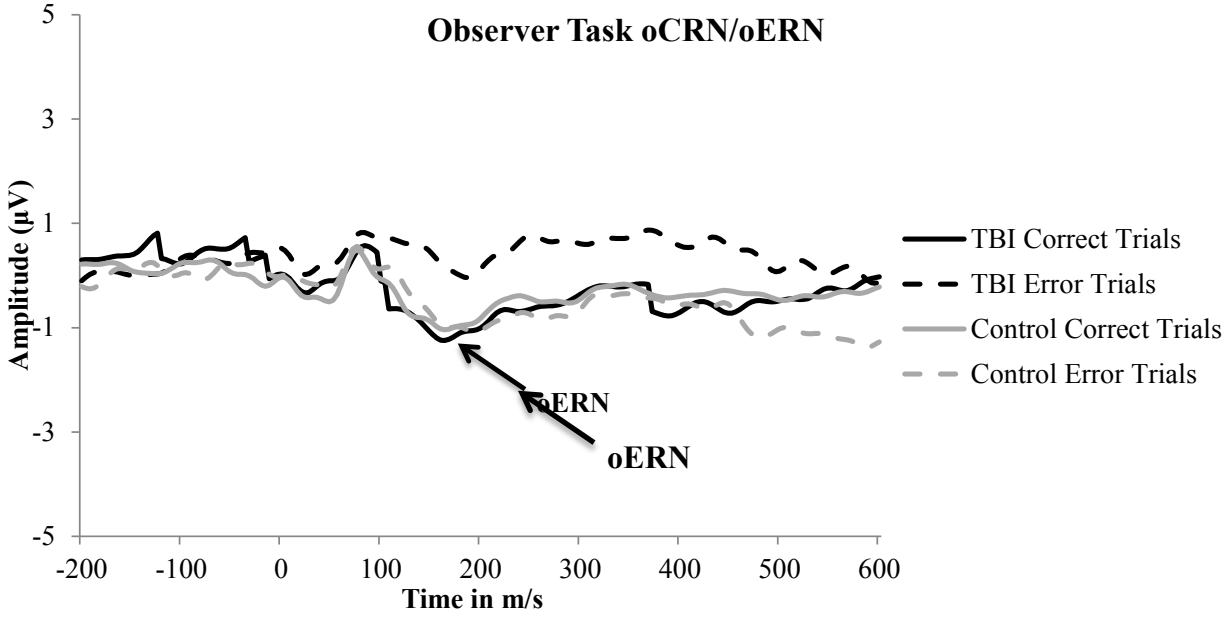

Figure 3. Grand average waveform for the Observer task oCRN/oERN.

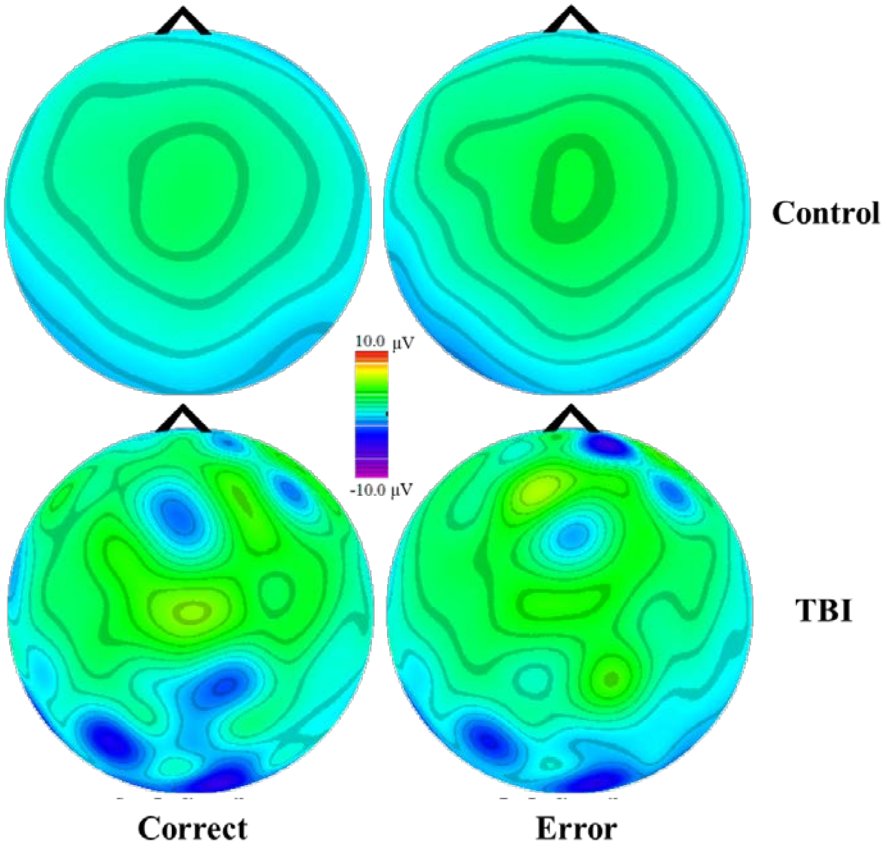

Figure 4. Topographical representation of oCRN/oERN voltages.

Discussion of Experiment 1

Results of the laboratory-based observer study were inconclusive, but suggest that the observer task was not effective in producing a reliable oERN in healthy controls or in individuals with M/S TBI. There was no significant main effect or interaction of accuracy on oERN amplitude or latency; however, participants did produce an observable negative going waveform similar to an oCRN. The lack of significant results was unexpected since accuracy effects on the oERN have been established in previous studies using a similar paradigm in healthy adults (Carp et al., 2009; de Bruijn & von Rhein, 2012; van Schie et al., 2004). It is possible that since neither

the control group nor the TBI group produced a measureable oERN that the null results were specific to the study sample or to subtle changes in the experimental task.

Comparison of the observer task used in this study to tasks used on previous oERN studies indicated some subtle differences in how the task was implemented. Miltner et al. (2004) and Bates, Patel, and Liddle (2005) used a choice reaction time task and a go/no go task respectively in their observer-based ERP tasks rather than a flanker task as used in this study. van Schie, Mars, Coles, and Bekkering (2004) and de Bruijn and von Rhein (2012), however, employed an Eriksen flanker task similar to that used in the observer experiment; however, the presentation of the task was slightly different. Observer information was presented on a second small LED screen and flanker arrows were not presented to observers. Researchers responded with exaggerated movements on two joysticks and participants in each study were asked to count the number of errors committed. van Schie et al. required participants to complete 1600 trials, 8 sets of 100 trials as a participant and 8 sets of 100 trials as an observer. Each set of trials was approximately 2 minutes long with a short break between each trial in which the participant reported the number of errors committed. de Bruijn and von Rhein used 2400 trials, 1600 as an observer and 1600 as the responder. Carp, Halenar, Quandt, Sklar, and Compton (2009) also used an Eriksen flanker task similar to that used in the current study. Presentation of the task was nearly identical to the task in the current study. The only exception was that participants were presented five groups of 100 trials with a short break between each set of trials. Mean errors included in subject average waveforms was 54 which is similar to that obtained in the observer task. Participants were also asked to count the number of errors committed and to report those errors at the end of each round.

The one consistent change between the current study task and the Eriksen flanker tasks reviewed above was that participants were not asked to count the number of error trials in the observer task for the current experiment and participants were not allowed frequent breaks. The decision to not have participants count trials was made based on the length of the task. In the current study, the observer task was only one element of an approximately three-hour experimental session. The task was limited to a 20-minute time block and a sufficient number of trails needed to be completed to preserve adequate signal to noise ratio. Maintaining the count information in working memory over the 20-minute time block with an impaired population could have distracted, encouraged inclusion of additional cognitive processes (repeating the count), and complicated interpretation of the task results. In addition, oERN findings by Bates et al. suggested that counting was not inherently necessary in order to produce an oERN. The observer task findings suggest that counting may be an important component in producing oERN waveforms on an Eriksen flanker task. Additional studies should use a count and no count condition to evaluate the effect of counting on the oERN.

The lack of long breaks in the current study could also have contributed to participant fatigue. Unfortunately, limited data is available to confirm participant concentration on the task. The lack of data makes it difficult to evaluate what role fatigue may have played. Overall, the lack of significant finding on the observer task was unexpected but not without possible explanations (see above). Future studies need to be conducted to evaluate what are necessary and/or sufficient elements to include in a study design in order to elicit a reliable oERN. In addition, studies could be conducted using tasks similar to that used by Miltner et al. (2004) or Bates et al. (2005) to evaluate if individuals with M/S TBI produce measureable and reliable

oERN components. In sum, however, Experiment 1 was not successful and did not produce the expected ERPs in either the control or TBI groups.

Specific Information for Experiment 2: The Picture Task

Method

Participants. Four participants were dropped from the TBI group on the Picture task due to insufficient number of error trials following EEG artifact correction and rejection. Total error trials usable in analyses on each of the four participants were 2, 0, 0, and 0. Three individuals were dropped from the control group, one due to insufficient trials (total error trials = 5) and two because of failure to complete survey data correctly. The final sample consisted of 32 individuals (12 female)—including 17 control participants and 15 individuals with TBI. A summary of demographic information for the task including between-group comparisons for experiment two are presented in Table 5.

Table 5

Demographics: Mean, Standard Deviation, and Range for the Picture Task.

	Control Group			TBI Group				
	Mean	(SD)	Range	Mean	(SD)	Range	*F*	*p*
Age	32.00	(9.80)	19 - 47	37.70	(10.91)	22 - 51	1.94	0.18
Education	15.59	(1.54)	13 - 18	15.67	(2.50)	11 - 21	0.01	0.92
NAART IQ	107.56	(7.66)	84 - 122	107.26	(6.99)	90 - 120	0.01	0.91
Sex	10 Male		7 Female	10 Male		5 Female	$\chi^2 = 0.21$	0.65

Estimated IQ = NAART Estimated Full Scale IQ

Picture Task. The Picture task was an adaptation of the task used by de Bruijn, Schubotz, and Ullsperger (2007). Participants observed 50 short action sequences of six pictures

each demonstrating various naturalistic actions such as making a sandwich or hammering a nail. Pictures were presented sequentially for approximately 500ms each. The initial six pictures were followed by a 1000ms fixation point. After the fixation stimuli, participants were shown a picture completing the action sequence with either a correct or an incorrect action (see Figure 5). For error trials the presented action sequence ended in an execution error (such as missing the nail with the hammer or dropping bread). Each action sequence had both a correct and an erroneous ending. Action sequences were displayed four times each with two correct and two erroneous versions producing a total of 200 trials. Each action sequence was separated by a blank screen with a fixation point for 1000 milliseconds.

Participants were instructed to count the number of action sequences that ended in errors and to report the number of errors counted at the end of the task. Error counts were used as a means of encouraging and verifying participant focus and concentration during picture observation.

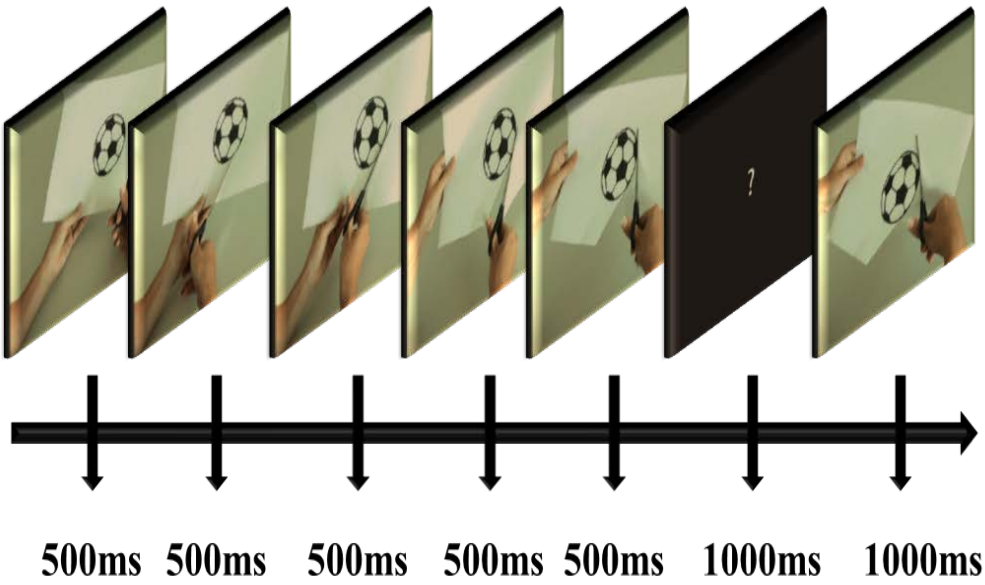

Figure 5. Example of EEG Picture Task Action Sequence

Results

Behavioral. Control and TBI groups did not significantly differ on the number of correct trials or error trials included in average ERP waveforms. Further, groups did not significantly differ on the number of picture trials identified as correct or error trials (see Table 6).

Table 6

Picture Tasks Behavioral Data

	Control Group			TBI Group				
	Mean	(SD)	Range	Mean	(SD)	Range	*F*	*p*
Correct Trials	81.47	(22.55)	24-97	79.47	(12.94)	54-97	0.09	0.76
Error Trials	81.12	(21.09)	28-97	80.20	(12.53)	60-99	0.02	0.88
Total Trials	162.60	(43.45)	52-190	159.67	(24.74)	123-194	0.05	0.82
Err Trials ID*	96.82	(4.85)	88-104	92.00	(12.15)	65-112	2.28	0.14

p = The calculated p-value between groups on a 2-tailed independent samples T-test

*Err Trials ID = Number of trials classified as error trials out of 100 possible errors

Two participants in the TBI group were identified as moderate outliers. One participant was an outlier on number of error trials identified. He correctly identified only 65 out of 100 presented error trials. His performance placed him beyond 1.5 interquartile ranges for the sample population on number of items correctly identified. Analyses with and without the first outlier data were conducted and showed no change in the general findings of the study. As a result, only the analyses including the outlier information are presented below. The second outlier produced data which placed her beyond 1.5 interquartile ranges on P300 amplitude and latency. Separate analyses with and without this outlier were conducted and differences between the

analyses were shown. Thus, both the results with and without this participant are presented below.

Self-Report Measures. A post-injury self-report of behavioral and cognitive functioning (FrSBe) indicated significant differences between controls and individuals with M/S TBI on scales of apathy, executive functioning, and total score (see Table 7). Individuals in the control and TBI groups also significantly differed on measures of anxiety and on measures of depression.

Table 7

Descriptive Statistics for Self Report Measures on the Picture Task

		Control Group			TBI Group				
		Mean	(SD)	Range	Mean	(SD)	Range	*F*	*p*
FrSBe	Apathy	26.47	(4.16)	21-34	36.27	(10.26)	20-56	13.14	0.001*
	Disinhibition	25.88	(5.67)	18-37	30.20	(9.72)	18-56	2.47	0.13
	Executive	31.88	(7.63)	19-45	44.80	(12.24)	27-76	13.17	0.001*
	Total Score	84.24	(15.38)	59-113	111.26	(65-188)	65-188	10.11	0.003*
HADS	Depression	5.47	(3.14)	1 - 10	8.07	(4.42)	3 - 15	4.41	0.04*
	Anxiety	2.12	(2.15)	0 - 8	6.6	(3.84)	0 - 15	13.83	0.001*

HADS = Hospital Anxiety and Depression Scale, FrSBe = Frontal Systems Behaviors Scale

*p = A significant p-value between groups on a one way ANOVA

Neuropsychological Measures. Cognitive factors such as memory, simple processing speed, verbal fluency, working memory, cognitive flexibility, and executive functioning were evaluated (see Table 8). Significant differences were found between control and TBI groups on three measures of cognitive functioning: category fluency (a measure of semantic verbal

fluency), the Digit Span Total Score (an indicator of working memory), and RAVLT Recognition (a measure of memory). Neuropsychological measures were used in the study as a means of examining and characterizing overall neuropsychological functioning between groups. They were not included in correlational analysis in order to limit the number of exploratory analysis conducted in the experiment and because groups were relatively equivalent on the majority of the neuropsychological measures.

Aim 1 and Aim 3: N1. Grand average waveforms and spline-interpolated voltage maps for stimulus-locked trials reflecting the parietal occipital N1 are shown below (see Figures 6 and 7). A parietal-occipital negative deflection was observed consistent with an expected N1 which peaked at a mean of 168 ms (*SD* 13.40, Range 148 – 188) on correct trials and 166 ms (*SD* 15.05, Range 148 – 189) on error trials when collapsed across groups. A 2 (Group) x 2 (Accuracy) repeated measures ANOVA on N1 amplitude indicated that there was no main effect of accuracy, $F(1,30) = 2.36$, $p = 0.14$, $\eta^2_p = 0.07$, and no Group x Accuracy interaction effect, $F(1,30) = 2.56$, $p = 0.12$, $\eta^2_p = 0.08$, on N1 amplitude. In addition, a 2 (Group) x 2 (Accuracy) repeated measures ANOVA on N1 latency showed no significant difference between groups. There was no significant main effect of accuracy on N1 latency, $F(1,30) = 0.04$, $p = 0.84$, $\eta^2_p = 0.001$, or Group x Accuracy interaction, $F(1,30) = 1.89$, $p = 0.18$, $\eta^2_p = 0.06$. These results are consistent with the idea that the N1 is an early sensory component that I did not expect to differentiate conditions. Further, the N1 did not significantly differentiate groups, suggesting that differences in early sensory processing did not account for any potential findings in later cognitive ERP components.

Table 8

Descriptive Statistics for Measures of Cognitive Functioning

	Control Group		TBI Group			
Measure	Mean	(SD)	Mean	(SD)	*F*	*p*
Estimated Full Scale IQ	107.57	(7.66)	107.26	(6.99)	0.01	0.91
Estimated Verbal IQ	105.61	(8.75)	105.26	(7.98)	0.01	0.91
Verbal Fluency_F	14.59	(3.92)	12.87	(5.08)	1.17	0.29
Verbal Fluency_A	12.29	(4.01)	11.27	(3.10)	0.64	0.43
Verbal Fluency_S	15.41	(3.50)	13.20	(3.75)	2.98	0.10
Verbal Fluency_Tot	42.29	(9.90)	37.33	(11.24)	1.76	0.20
Verbal Fluency_Category	24.35	(4.82)	18.67	(6.30)	8.34	0.007*
AVLT_I	6.65	(1.58)	6.40	(2.69)	0.10	0.75
AVLT_II	9.82	(2.24)	8.67	(2.94)	1.59	0.22
AVLT_III	11.29	(2.39)	9.47	(3.56)	2.97	0.10
AVLT_IV	12.35	(1.46)	11.67	(2.58)	0.89	0.36
AVLT_V	12.24	(1.48)	11.53	(3.27)	0.64	0.43
AVLT_Total_Learning	52.35	(7.56)	47.73	(11.69)	1.81	0.19
AVLT_B	6.88	(1.45)	5.73	(2.31)	2.90	0.10
AVLT_Recall	10.53	(2.50)	8.93	(4.96)	1.37	0.25
AVLT_Delay	10.47	(2.60)	8.80	(4.39)	1.76	0.19
AVLT_Recognition	14.18	(1.13)	12.71	(2.67)	4.20	0.05*
Digit_Forward	10.35	(1.97)	10.47	(3.02)	0.02	0.90
Digit_For_Longest	6.71	(1.05)	6.87	(1.60)	0.12	0.74
Digit_Backward	7.53	(2.53)	7.40	(3.18)	0.02	0.90
Digit_Back_Longest	5.52	(1.33)	5.20	(1.52)	0.43	0.52
Digit_Sum	13.06	(2.93)	17.87	(5.77)	9.17	0.005*
Trails_A_Time	19.00	(7.47)	24.20	(11.72)	2.30	0.14
Trails_A_Errors	0.41	(0.51)	0.33	(0.62)	0.16	0.70
Trails_B_Time	50.18	(16.30)	75.00	(73.22)	1.86	0.18
Trails_B_Errors	0.24	(0.44)	0.93	(1.67)	2.77	0.11

* Correlation is significant at the 0.05 level (2-tailed).

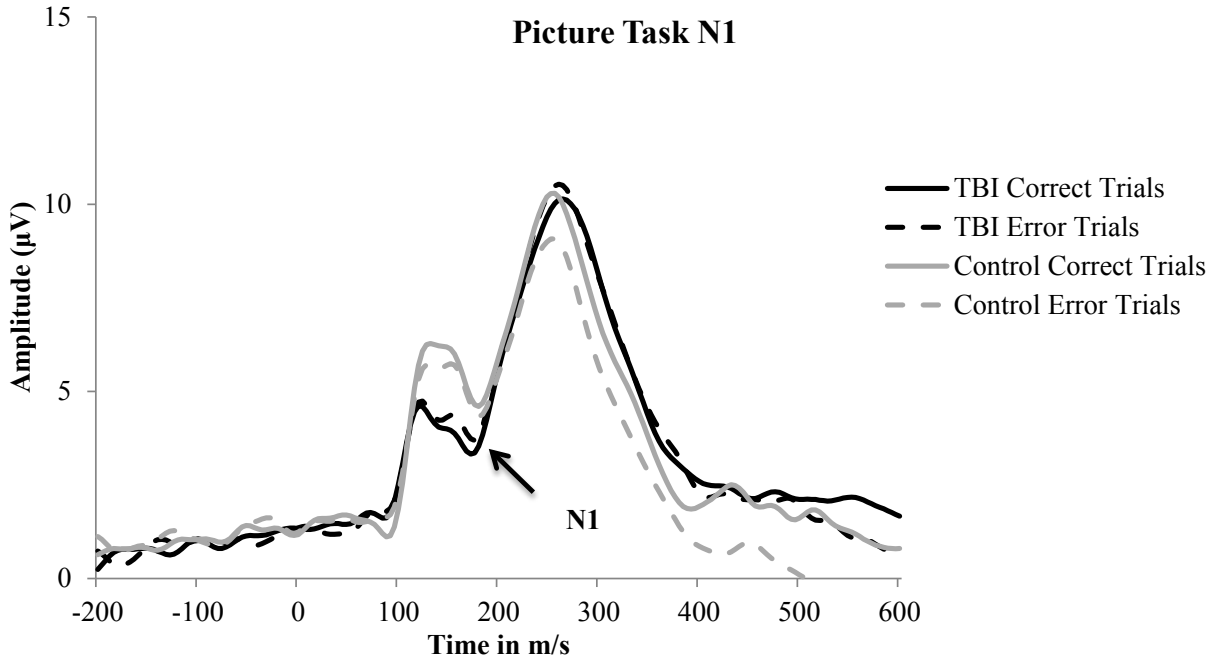

Figure 6. Waveform of the N1.

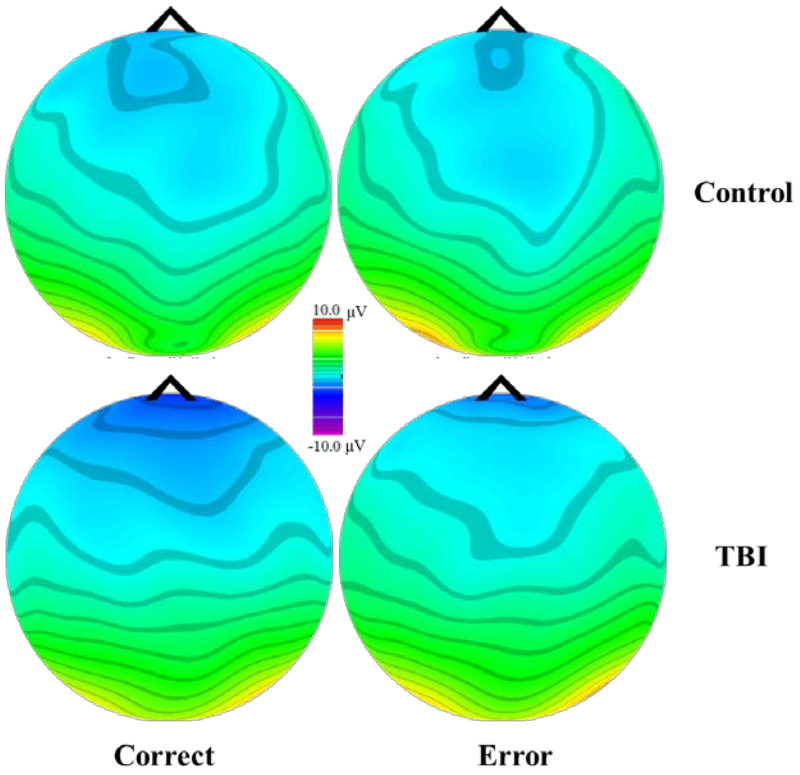

Figure 7. Topographical representation of N1 voltages for correct and error trials.

Aim 1 and Aim 3: P300. When collapsed across groups, stimulus-locked ERPs averaged across parietal occipital electrodes showed a positive deflection with a mean peak at 273 ms (*SD* 34.75, Range 248 – 432) for correct trials and 291 ms (*SD* 62.76, Range 248 – 511) for error trials, and appeared consistent with the P300 (see Figures 8 and 9). A 2 (Group) x 2 (Accuracy) repeated measures ANOVA demonstrated no significant main effect of accuracy on P300 amplitude, $F(1,30) = 3.11$, $p = 0.08$, $\eta^2_p = 0.09$; however, this was qualified by a significant Group x Accuracy interaction, $F(1,30) = 10.31$, $p = 0.003$, $\eta^2_p = 0.27$. Controls demonstrated a significant decrease in P300 amplitude on a paired samples *t*-test, $t(16) = 3.35$, $p = 0.004$, with smaller P300 amplitudes for error trials versus correct trials. The TBI group demonstrated no significant difference between error and correct trials, $t(14) = -1.11$, $p = 0.29$. Between-group comparisons, however, indicated no significant difference between the control group and TBI group on correct trials, $F(1,30) = 0.27$, $p = .87$, or for error trials, $F(1,30) = 1.31$, $p = 0.26$.

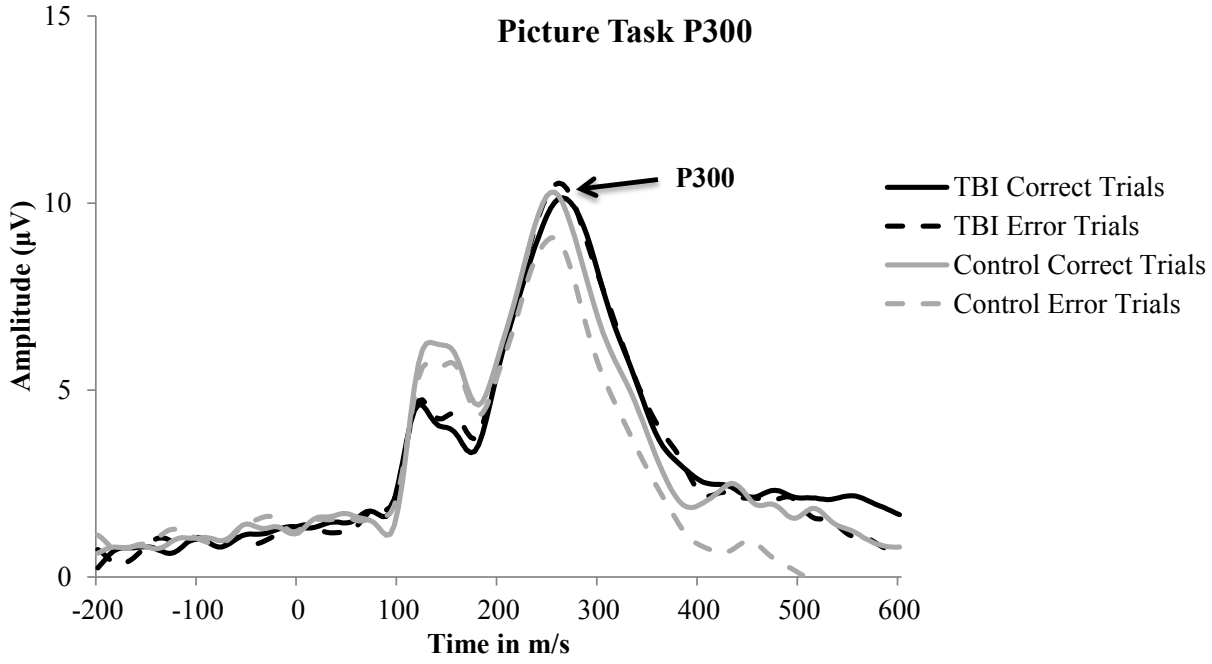

Figure 8. P300 Waveform.

A 2 (Group) x 2 (Accuracy) repeated measures ANOVA using P300 centroid latency demonstrated a main effect of accuracy, $F(1,30) = 8.64$, $p = 0.006$, $\eta^2_p = 0.22$, with error trials producing a faster latency time than correct trials. There was also a Group x Accuracy interaction, $F(1,30) = 4.36$, $p = 0.05$, $\eta^2_p = 0.13$. A paired sample *t*–test revealed that the control group showed significantly faster P300 centroid latencies on error trials in comparison to correct trials, $t(1,16) = 2.92$, $p = 0.01$. The TBI group demonstrated no significant change in centroid latency between error and correct trials, $t(14) = 1.01$, $p = 0.33$. Between group comparisons demonstrated no difference between control and TBI groups on correct trials, $F(1,30) = 0.07$, $p = 0.79$, or on error trials, $F(1,30) = 1.47$, $p = 0.23$.

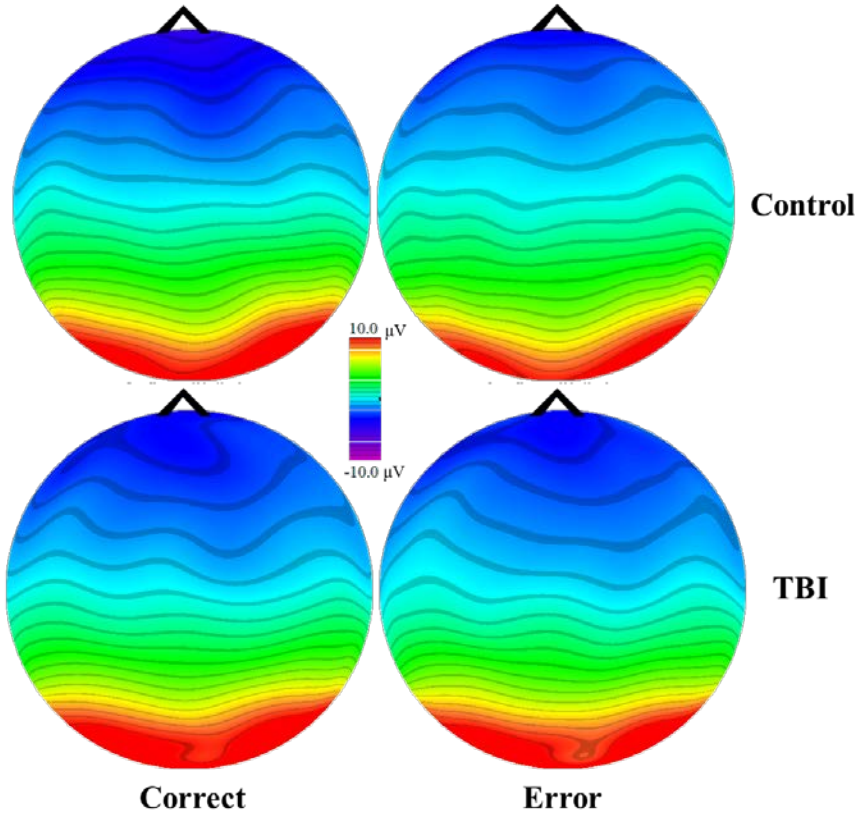

Figure 9. Topographical representation of P300 voltages for correct and error trials.

Removal of the outlier for P300 amplitude and latency did not significantly affect the general findings for P300 amplitude. However, removal of the outlier led to the emergence of a statistically significant main effect of accuracy for P300 latency, $F(1,29) = 7.76$, $p = 0.009$, $\eta^2_p = 0.21$, and a statistically significant Group x Accuracy interaction, $F(1,29) = 4.30$, $p = 0.05$, $\eta^2_p = 0.13$. Decomposition of the interaction effect using a one-way ANOVA indicated a significant difference between the control and TBI group for P300 centroid latency on error trials, $F(1,29) = 4.86$, $p = 0.04$, but not on correct trials, $F(1,29) = 2.35$, $p = 0.14$ (see Figure 10 and 11). Paired samples *t*–tests continued to demonstrate no significant difference on P300 latency between error and correct trials in the TBI group, $t(1,13) = 0.82$, $p = 0.43$. A paired sample *t*–test revealed that the control group showed significantly faster P300 centroid latencies on error trials in comparison to correct trials, $t(1,16) = 2.92$, $p = 0.01$.

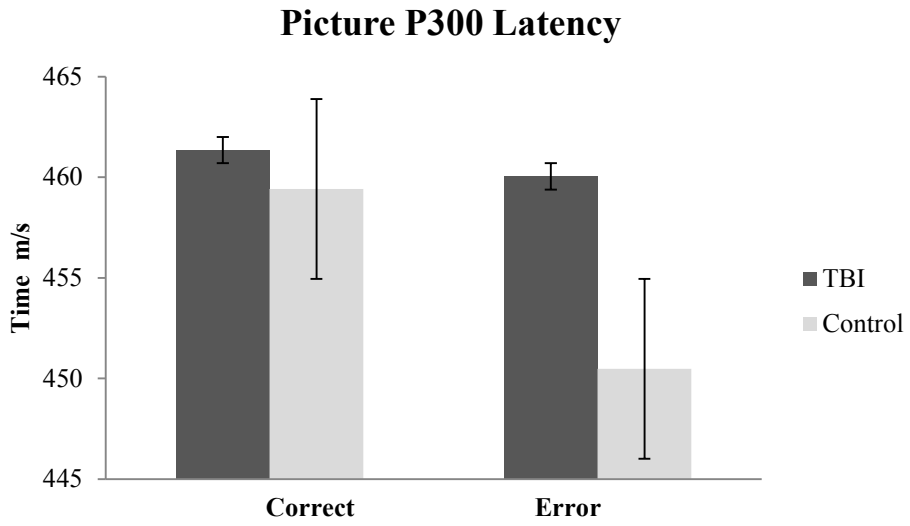

Figure 10. Comparison of P300 Centroid Latency by Group with Standard Error Bars.

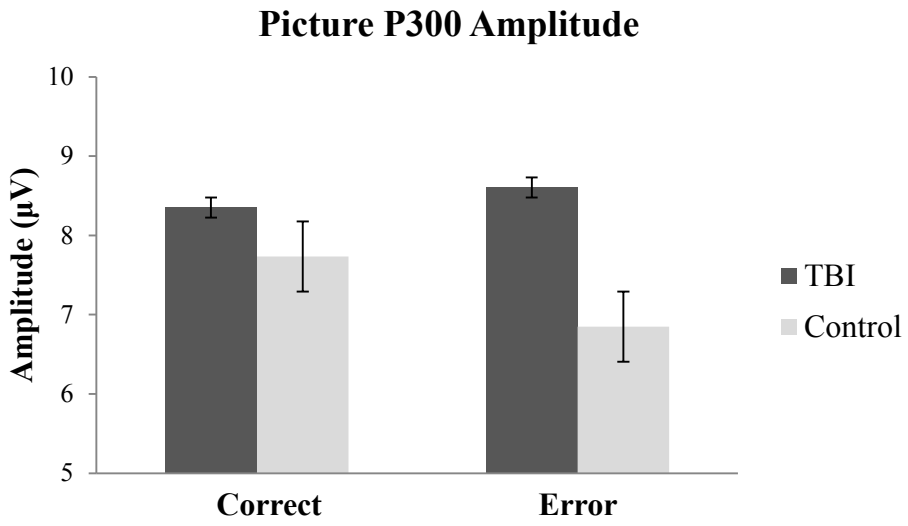

Figure 11. Comparison of P300 Amplitude by Group with Standard Error Bars.

Correlations. I also correlated self-reported levels of executive functioning (FrSBe) with P300 amplitude and centroid latency (See Table 9). As noted above, correlational data were exploratory in nature and alpha levels were not adjusted. Exploration of the correlations demonstrated that correlations between the P300 and participant scores on the FrSBe in the TBI group were unusually high, and strongly affected by the single outlier on P300 amplitude and latency in the TBI group identified above.

Removal of the outlier reduced the strength of correlations between groups leaving a moderate correlation in the TBI group between reported functioning on the FrSBe and P300 amplitude for error trials (see Tables 10 and 11 and Figures 12 - 19). The figures and tables below do not include the outlier data. Correlations suggested that for individuals with M/S TBI P300 amplitudes on error trials decreased as self-reported difficulties in areas of apathy, disinhibition, and executive functioning increased. In other words, as reported behavioral difficulties increased, P300 amplitude decreased.

A Fisher's r-to-z transformation was completed for all correlations comparing P300 with the FrSBe to determine if differences in correlations between the control and TBI groups were statistically significant. Statistically significant results would lend support to the idea that correlations between P300 and self-reported behavioral difficulties on the FrSBe are interpretable as between group interactions for the variables of interest. Results including the outlier data showed that correlations on P300 amplitude significantly differed between groups. Amplitude on the P300 was related to apathy and disinhibition while P300 latency was related to executive functioning in the TBI group (See Table 12).

Results of the Fisher's r-to-z analysis indicated that none of the correlations between groups were statistically significant with the outlier data removed. As a result no table is supplied. The results indicate that differences between healthy controls and individuals with M/S TBI without the outlier data were small enough that rejecting the null hypothesis of no group difference was not appropriate. Thus, the correlation results may not represent actual differences between groups on how the P300 indexes self-reported executive functioning.

Table 9

Zero Order Correlations for P300 and FrSBe Subscales for the TBI Group (N=15)

	1	2	3	4	5	6	7	8
1. P300 Correct Amplitude	1							
2. P300 Error Amplitude	0.96**	1						
3. P300 Correct Latency	0.72**	0.71**	1					
4. P300 Error Latency	0.77**	0.75**	0.93**	1				
5. Apathy	-0.67**	-0.69**	-0.53*	-0.58*	1			
6. Disinhibition	-0.72**	-0.70**	-0.66**	-0.71**	0.83**	1		
7. Executive Functioning	-0.68**	-0.70**	-0.62*	-0.62*	0.89**	0.94**	1	
8. Total Score	-0.72**	-0.72**	-0.63*	-0.66**	0.94**	0.96**	0.99**	1

* Correlation is significant at the $p < 0.05$ level (2-tailed).

** Correlation is significant at the $p = < 0.01$ level (2-tailed).

Table 10

Zero Order Correlations for P300 and FrSBe Subscales for the Control Group (N=17)

	1	2	3	4	5	6	7	8
1. P300 Correct Amplitude	1							
2. P300 Error Amplitude	0.96**	1						
3. P300 Correct Latency	0.35	0.31	1					
4. P300 Error Latency	0.61**	0.56*	0.41	1				
5. Apathy	-0.07	-0.06	-0.27	0.04	1			
6. Disinhibition	-0.09	-0.11	-0.08	-0.15	0.55*	1		
7. Executive Functioning	-0.12	-0.12	0.25	0.09	0.70**	0.68*	1	
8. Total Score	-0.11	-0.11	0.09	0.00	0.82**	0.86**	0.94**	1

* Correlation is significant at the $p < 0.05$ level (2-tailed).

** Correlation is significant at the $p = < 0.01$ level (2-tailed).

Table 11

Zero Order Correlations for P300 and FrSBe Subscales for the TBI Group Outlier Removed (N=14)

	1	2	3	4	5	6	7	8
1. P300 Correct Amplitude	1							
2. P300 Error Amplitude	0.95**	1						
3. P300 Correct-Latency	0.50	0.59*	1					
4. P300 Error-Latency	0.60*	0.66*	0.80**	1				
5. Apathy	-0.52	-0.56*	-0.19	-0.30	1			
6. Disinhibition	-0.53	-0.56*	-0.22	-0.30	0.77**	1		
7. Executive Functioning	-0.46	-0.56*	-0.11	-0.14	0.86**	0.88**	1	
8. Total Score	-0.53	-0.59*	-0.18	-0.26	0.94**	0.92**	0.97**	1

* Correlation is significant at the $p < 0.05$ level (2-tailed).

** Correlation is significant at the $p = < 0.01$ level (2-tailed).

Table 12

Fisher r-to-z Transformation for Zero Order Correlations of P300 and FrSBe Showing p-value of Between Group Differences

	1	2	3	4	5	6	7	8
1. P300 Correct Amplitude	*p*-value							
2. P300 Error Amplitude	#	*p*-value						
3. P300 Correct-Latency	#	#	*p*-value					
4. P300 Error-Latency	#	#	#	*p*-value				
5. Apathy	0.06	0.05*	0.42	0.07	*p*-value			
6. Disinhibition	0.04*	0.05*	0.07	0.06	#	*p*-value		
7. Executive Functioning	0.07	0.06	0.01**	0.04*	#	#	*p*-value	
8. Total Score	0.04*	0.04*	0.03*	0.04	#	#	#	*p*-value

* Correlation is significant at the $p < 0.05$ level (2-tailed).

** Correlation is significant at the $p = < 0.01$ level (2-tailed).

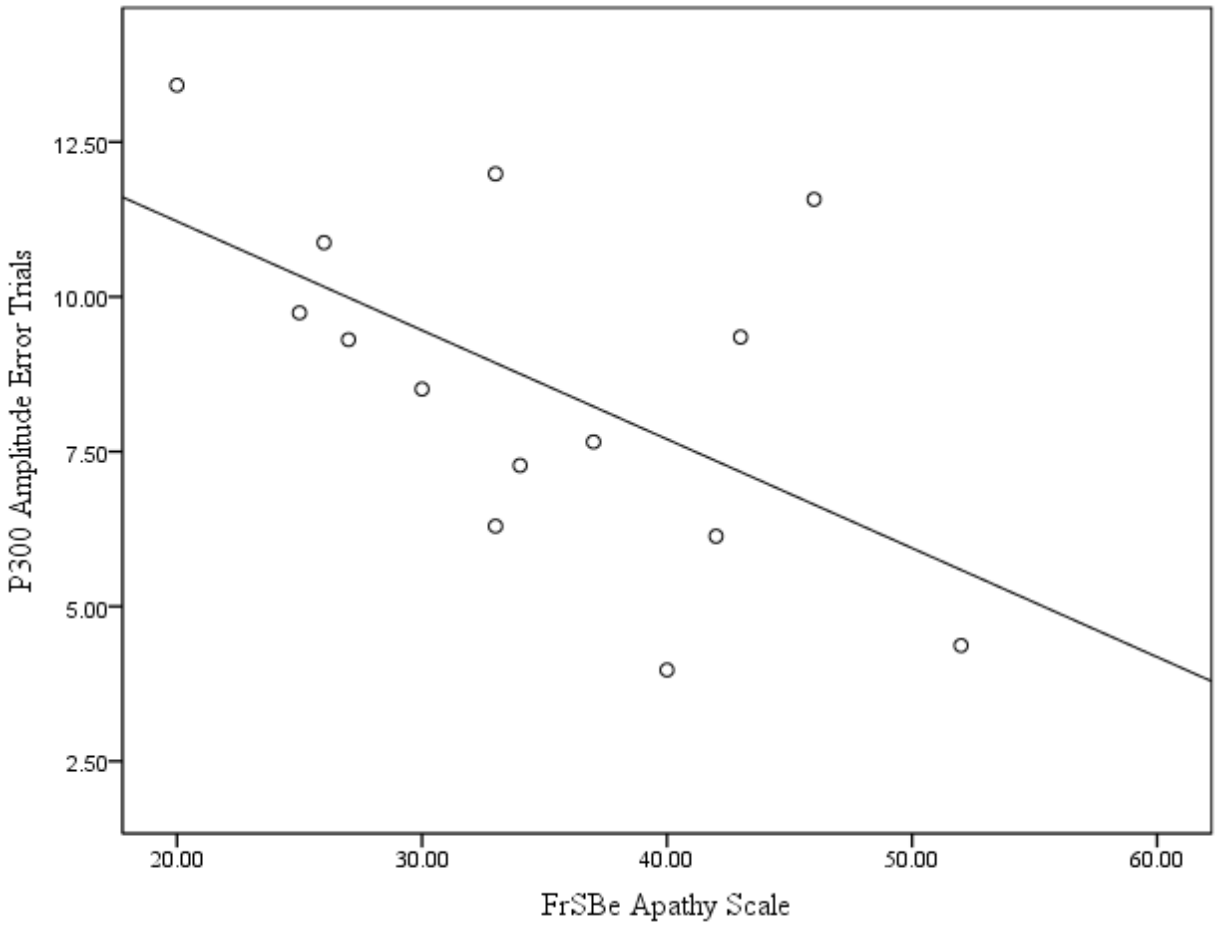

Figure 12. Scatterplot of FrSBe Apathy and P300 Amplitude for the TBI group.

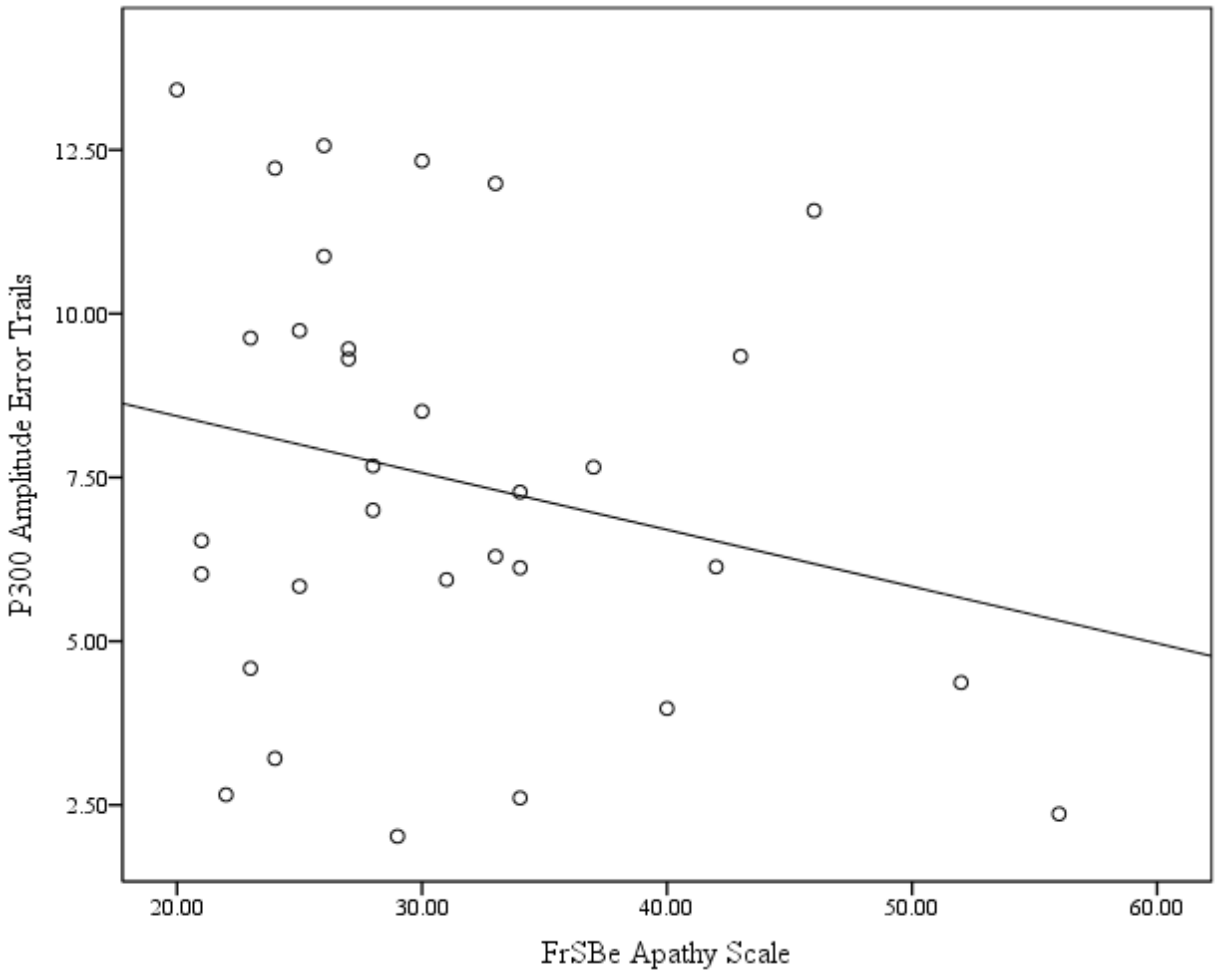

Figure 13. Scatterplot of FrSBe Apathy and P300 Amplitude for the Control group.

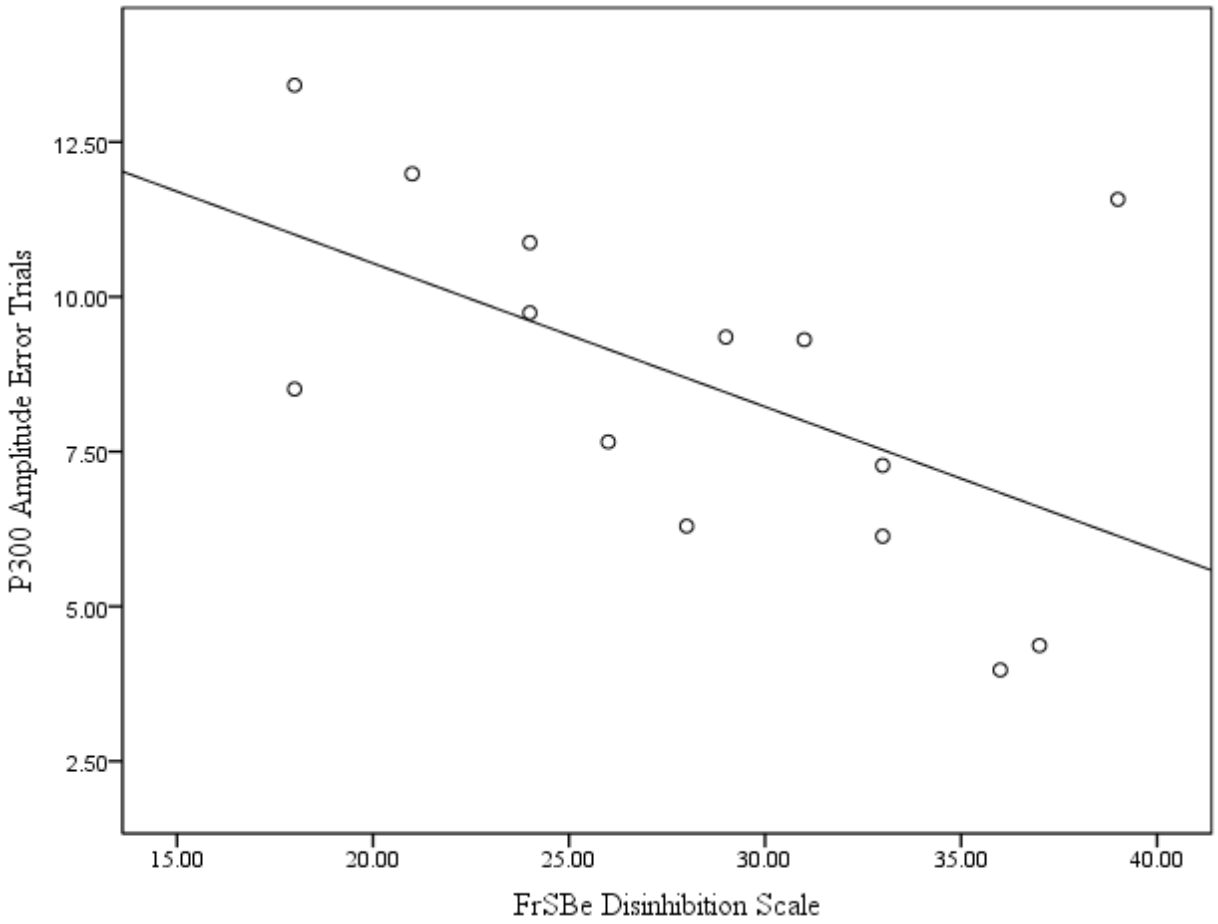

Figure 14. Scatterplot of FrSBe Disinhibition and P300 Amplitude for the TBI group.

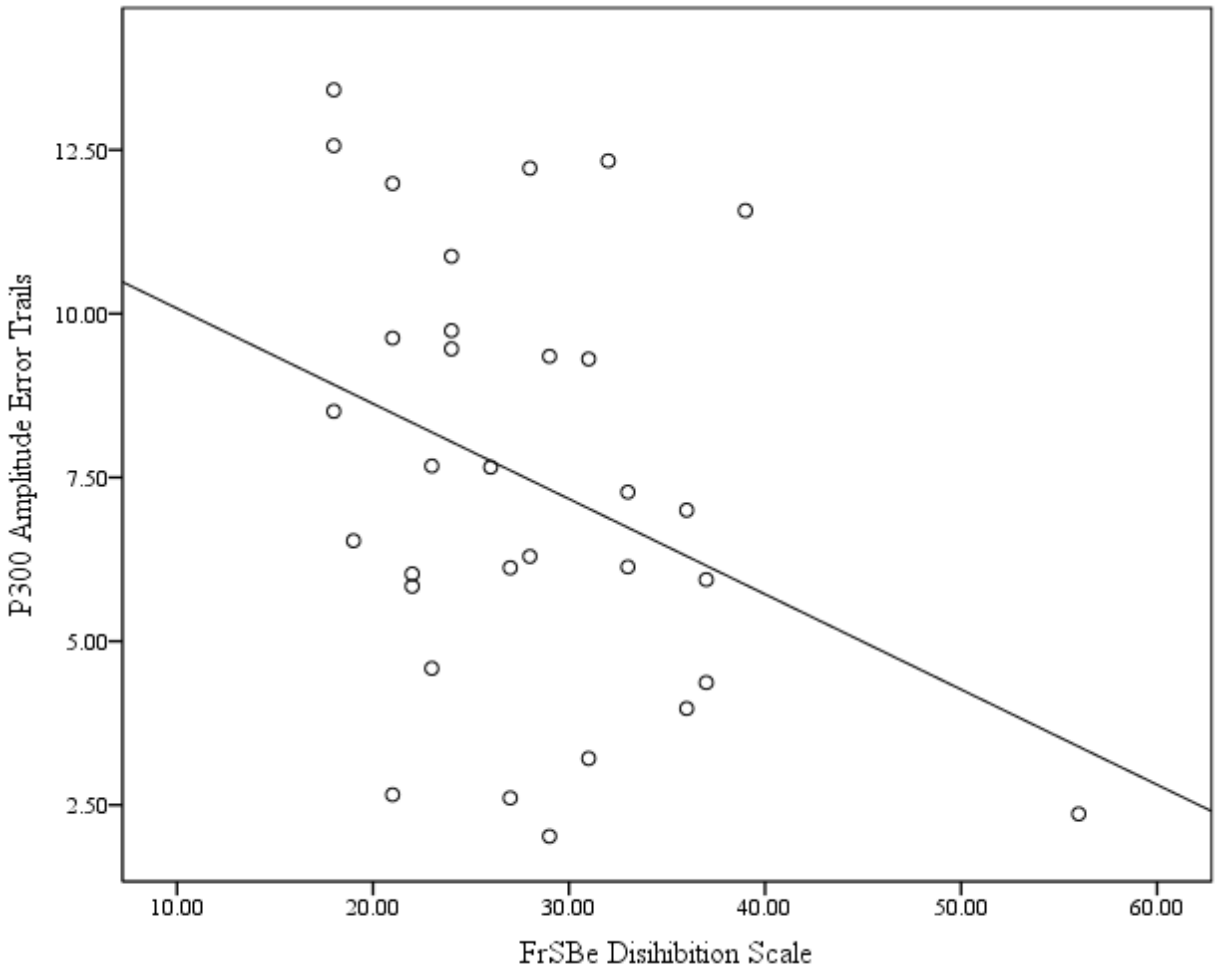

Figure 15. Scatterplot of FrSBe Disinhibition and P300 Amplitude for the Control group.

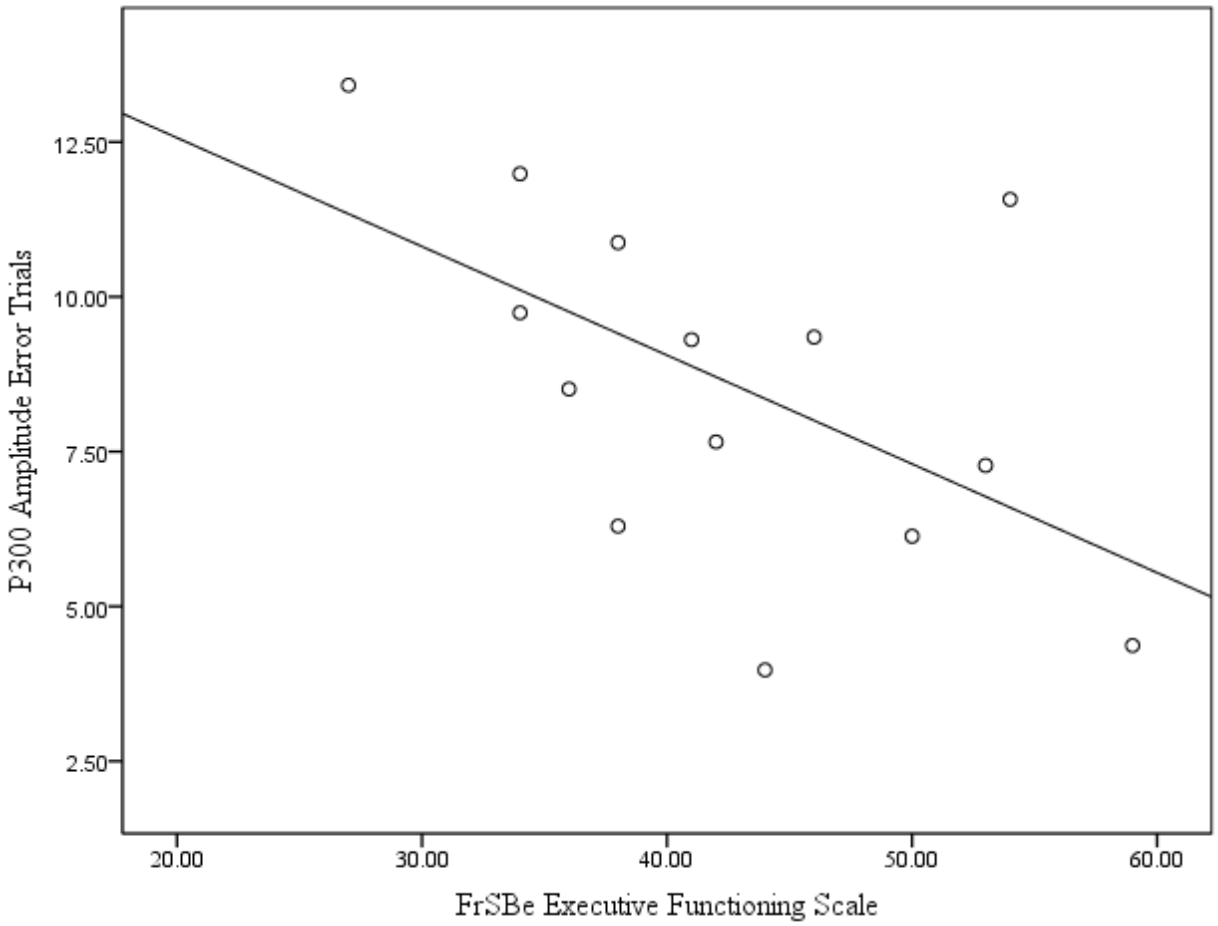

Figure 16. Scatterplot of FrSBe Executive Functioning and P300 Amplitude for the TBI group.

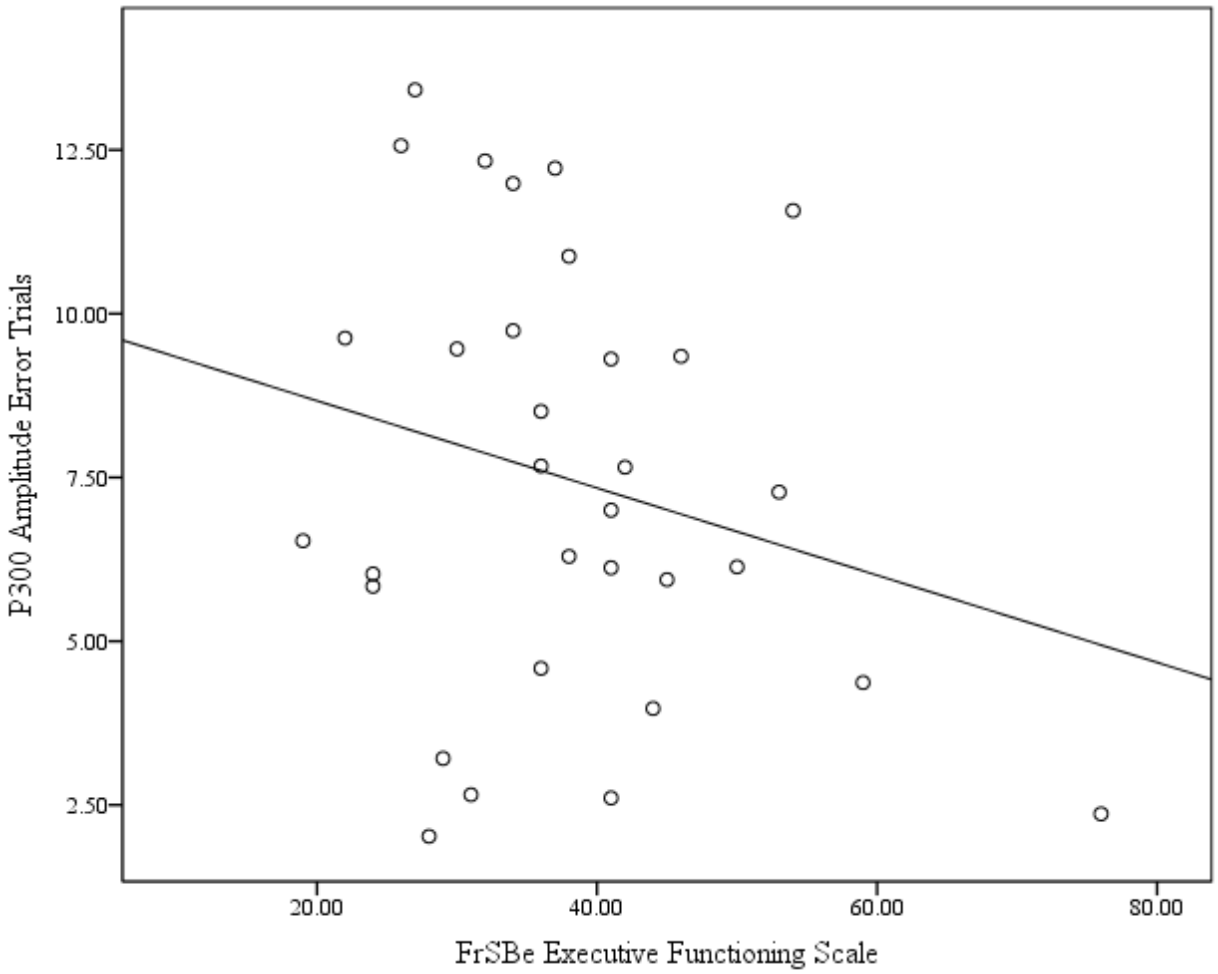

Figure 17. Scatterplot of FrSBe Executive Functioning and P300 Amplitude for the Control group.

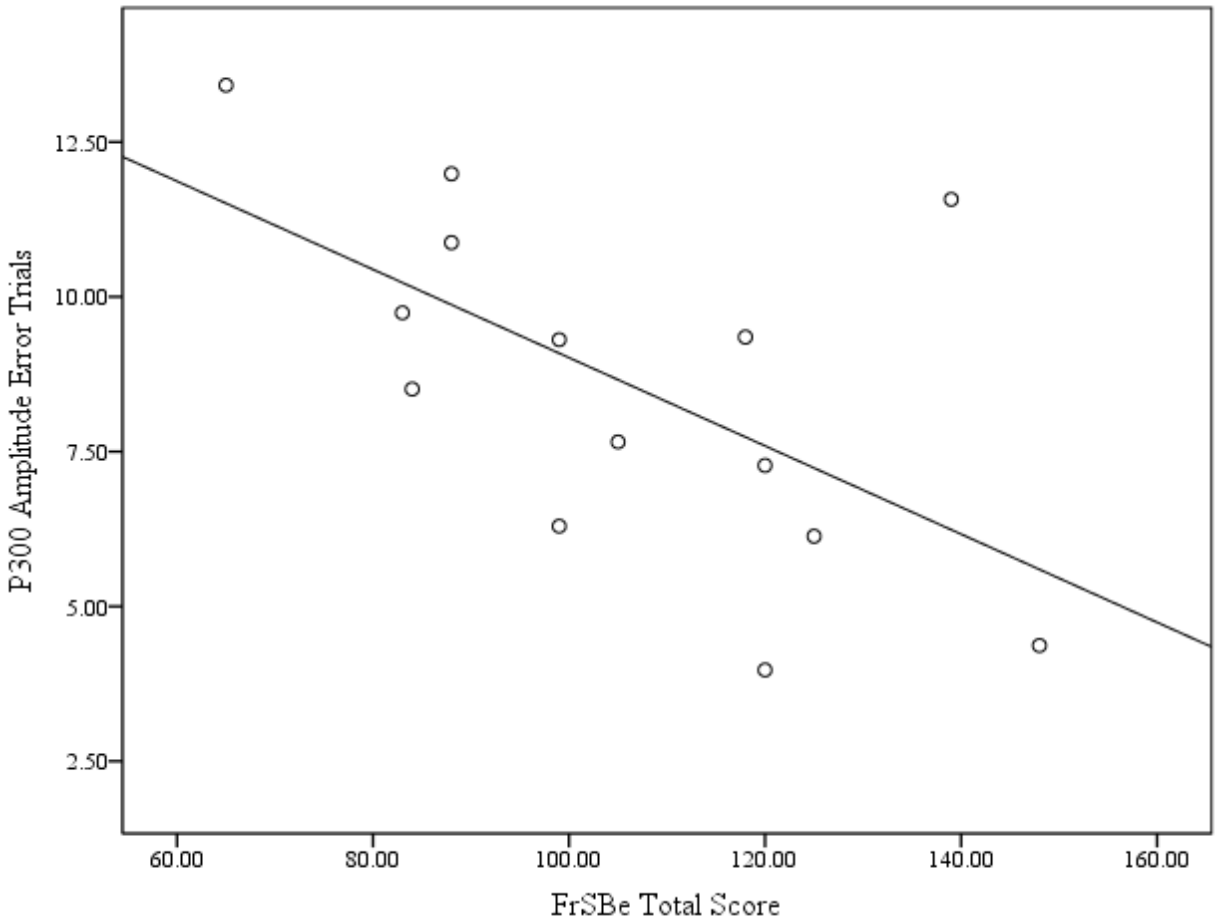

Figure 18. Scatterplot of FrSBe Total Score and P300 Amplitude for the TBI group.

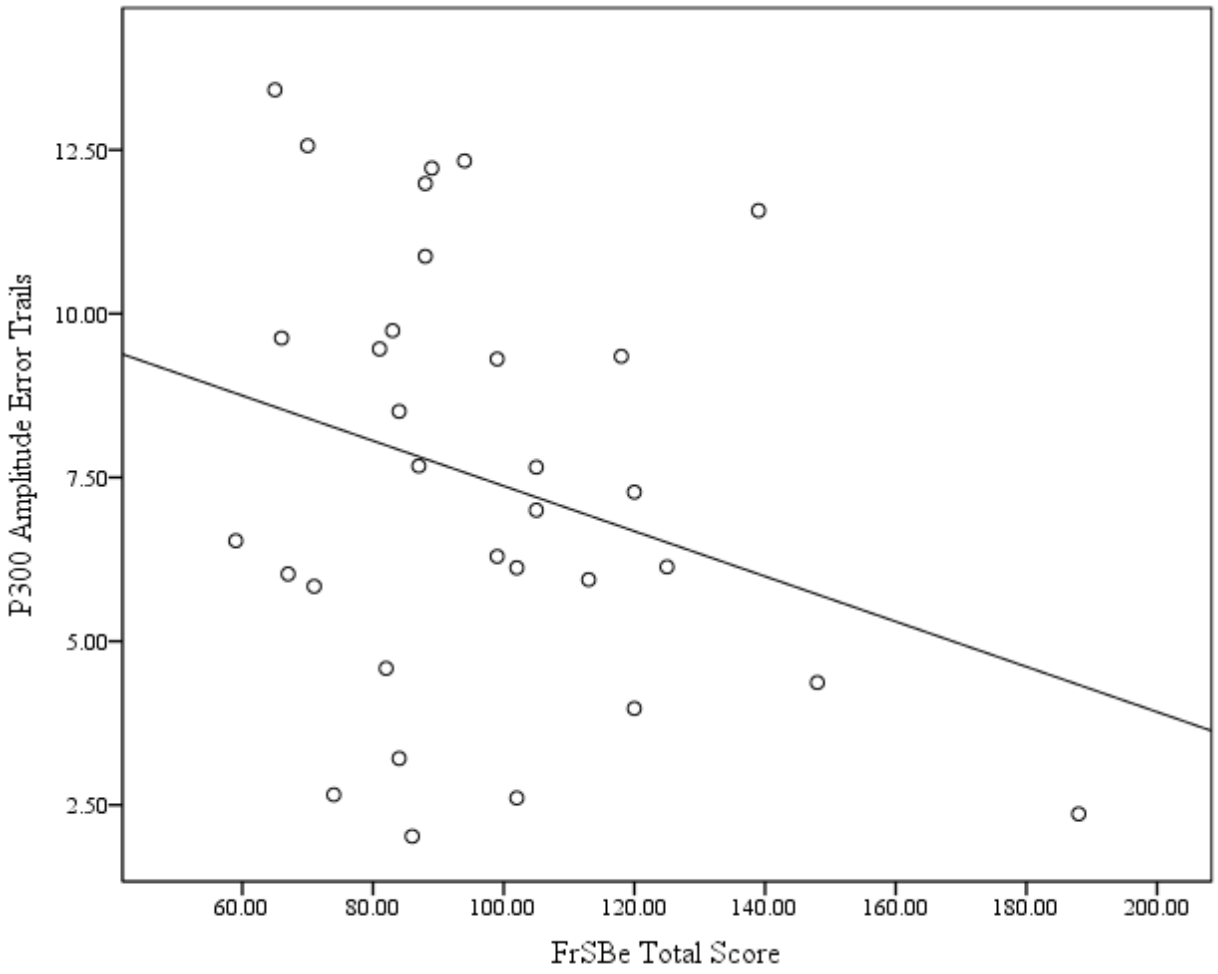

Figure 19. Scatterplot of FrSBe Total Score and P300 Amplitude for the Control group.

Discussion of Experiment 2

The initial hypothesis for the picture task was that P300 amplitude would be smaller and P300 latency would be slower for individuals in the TBI group compared to the health control group. The initial hypothesis was based on previous research (Bashore & Ridderinkhof, 2002; Duncan et al., 2003; Duncan, Summers, Perla, Coburn, & Mirsky, 2011; Lew et al., 2004) but was not accurate for the study sample. On correct trials individuals with M/S TBI produced a P300 component that was not significantly different compared to controls. The most likely

explanation for a similar P300 was the chronic status of individuals with M/S TBI in the current study sample. As mentioned in the introduction, two research groups found that as time since injury increased, differences between controls and individuals with TBI on P300 amplitude and latency decreased (Bashore & Ridderinkhof, 2002; Cremona-Meteyard & Geffen, 1994). Thus, a lack of significant differences between groups on correct trials on both amplitude and latency can be understood in the context of time since injury as the current sample is very chronic and has an extended time since injury.

Another unusual finding in the current study was that controls produced P300s with faster latency and smaller amplitude when presented with error trials than when presented with correct trials. Individuals with M/S TBI did not demonstrate the same effect despite correctly classifying an equal number of error trials. If recorded latency differences were based on processing speed controls would have demonstrated faster latency times than individuals with M/S TBI on both error and correct trials. This was not the case. Amplitude differences also suggested a divergence between groups on error trials.

The results suggest several interesting possibilities. First, de Bruijn et al. (2007) in their initial paper evaluating naturalistic actions in healthy adults raised the prospect of two routes or pathways for classifying information in the brain, with more complicated error information being processed differently than less complex information. In the current study, error trial information appeared to be processed more efficient or rapidly than correct trial information. If, as de Bruijn et al. (2007) suggested, a second process for evaluating errors existed, it would appear to be compromised in individuals with M/S TBI. As a result, while participants with M/S TBI were able to effectively classify errors at the same accuracy level as controls, they did not expedite the information for rapid processing.

Some caution is suggested in accepting the hypothesis of a second more rapid pathway for processing errors which affects P300 amplitude. The current study is only the second study to provide evidence suggesting an alternate strategy for classifying different types of error related information (de Bruijn et al., 2007). Considerable research would still have to be completed before a dual process hypothesis could be substantiated.

Another possibility for explaining the results of the current study has to do with the nature of the presented stimuli. Laboratory based tasks using tones, colors, or simple symbols commonly used in studying the P300 generally find an increase in P300 amplitude for target items (See Duncan-Johnson & Donchin, 1977 and Polich & Comerchero, 2003 for a comprehensive review). Activities presented on the picture task were purposefully designed to be easily identified and rapidly categorized. I wanted to minimize the complexity of the neural processes required to avoid masking difference in ERPs with unrelated neuronal activation; however, in comparison to typical laboratory tasks, which use stick figures or simple symbols, the nature of the picture stimuli were relatively complex (e.g., a picture taken of people accidentally missing a soccer ball when attempting to kick it).

Polich and Comerchero (2003) compared P300 latency and amplitudes on a simple discrimination task and on a complex discrimination task using simple and complex symbols. They found that on the complex task P300 amplitude was smaller for target items (error trials in the context of the current study) than for non-target items (correct trials) and that P300 latency was shorter for target as opposed to non-target items. The findings of the present study closely mirror these results in the healthy control group; however, in individuals with M/S TBI no differences on P300 amplitude and latency were apparent in how task items were classified. Again supporting an unusual deviation in how individuals with M/S TBI processed the

information. If changes in P300 amplitude and latency were attributed to stimulus complexity than it would mean individuals in the control group appropriately modified neuronal activation in order to adapt to complex tasks. Individuals with M/S TBI did not significantly modify their approach to complexity, supporting a divergence in how individuals with M/S TBI responded to the task. Inadequate modification of neuronal process would place individuals with M/S TBI at increased risk of erroneous application of regulative process possibly leading to increased errors. Future research to provide evidence for the role of complexity in errors following M/S TBI could compare individuals with M/S TBI to controls on naturalistic action tasks of increasing complexity or attempt to measure both ERPs and naturalistic actions on simple and complex tasks to see if changes in P300 amplitude would correlate with behavioral errors.

The results of the picture task suggest some interesting possibilities for understanding naturalistic action errors following M/S TBI. Unfortunately, a lack of consistency with de Bruijn et al.'s (2007) findings needs to be addressed. Task related differences likely explain the discrepancy in results and stimulus complexity again offers an elegant explanation. de Bruijn et al.'s results are most consistent with results from simple go no\go tasks or oddball tasks which demonstrate larger P300 amplitude elicited by target items compared to non-target items (Duncan-Johnson & Donchin, 1977, 1982; Duncan, Barry, Connolly, Fischer, Michie, Näätänen, et al., 2009; Hajcak et al., 2010; Johnson & Donchin, 1980; Polich, 2007). The reversal of the results compared to de Bruijn et al is consistent with previous research demonstrating a reduction in P300 amplitude to target items in difficult or complex categorization tasks as opposed to simpler categorization tasks (Polich & Comerchero, 2003).

Despite the fact that the results of de Bruijn et al. (2007) fit well in the context of simple item categorization tasks, there is some evidence to suggest an error connected component to the

findings. In simple categorization tasks such as a go no/go tasks, 50/50 presentation of target and non-target items produces a non-significant difference between amplitude of the P300 for target and non-target items , or no P300 is produced at all with only stimulus related components such as the N1 and N2 components being produced (Polich, 2007; Polich & Criado, 2006). de Bruijn et al.'s naturalistic error task produced a robust difference in P300 amplitude for error and correct trials despite the 50/50 presentation suggesting that accuracy was being indexed by the P300 regardless of item probability. In the current task a similar phenomenon occurred. In the current picture task error and correct trial information was presented with 50/50 probability and still produced significant accuracy related differences in the control group.

Both finding fit well within the inhibition model of the P300 (Polich, 2007, 2010). Polich proposed that the P300 represents the activation of cognitive control marked by PFC inhibition of neuronal activity as a means of suppressing unnecessary information. The result is to speed processing of task relevant events from frontal to parietal systems. To explain the effect of task complexity on P300 amplitude Polich suggested that simple tasks allow for the suppression of a large number of neurons and thus produce a larger P300 for target items. In contrast more complex tasks require a large number of neurons and may require additional resources to transfer information from frontal systems to temporal parietal systems. The result is a smaller P300 for the task in general and a somewhat counterintuitive reduction of inhibition as a large amount of neurons are recruited to a single task and do not require inhibition. Explaining the lack of change in individuals with M/S TBI is somewhat more problematic. The lack of change could suggest similar levels of top down inhibition being needed to eliminate noise related to neuronal damage. Increased inhibition would slow processing as less resources would be available and

would explain the significantly slowed P300 latency of individuals with M/S TBI compared to controls on error trials.

Another important component of evaluating P300 differences between groups is to evaluate if the P300 meaningfully indexed real world functioning for individuals with M/S TBI. Again, the purpose of the experiment was to expand current understanding about increased naturalistic action errors following M/S TBI. The results suggested that individual in the M/S TBI group who reported greater functional impairment also demonstrated smaller P300 amplitudes. Correlations including the outlier data were quite large and suggested that the P300 did index real world changes in functioning. Unfortunately, the correlational results were largely attenuated after removing the outlier. The correlations were not large enough to suggest statistically significant differences between groups. As a result the correlations were unable to lend support to the idea that P300 amplitude indexed neurological changes specific to M/S TBI that were correlated with real world functioning.

In all, the picture task succeeded in eliciting a P300 which varied in relation to accuracy across trials. Differences between groups in ERP response to the picture task suggested various avenues of future research for better understanding increased naturalistic action errors for individuals with M/S TBI. Equivalent N1 amplitude between groups supplied additional evidence that P300 amplitude differences were not simply the result of generalized processing changes but specific differences in how individuals with TBI processed the picture task.

General Discussion

The purpose of this dissertation was to expand understanding of error related behavioral deficits following M/S TBI by evaluating one possible method of bridging the gap between laboratory-based tests and measures focused on more naturalistic activities. The proposed

method was to use observed errors while recording ERPs as a means of bridging the gap. The hypotheses of the study were: (1) That individuals with M/S TBI would reliably produce error related ERPs during the observation of errors; (2) That individuals with M/S TBI would have a reduced error-related neurophysiologic reaction to error observation on a standard error task compared to controls; and (3) Individuals with M/S TBI would demonstrate a reduced neurophysiologic reaction to observed naturalistic errors when compared with healthy controls.

The results of the current study were mixed in helping to evaluate the hypothesis presented above. First, the observer task failed to elicit error related ERPs from both control participants and individuals with M/S TBI. As a result, Aim 1 and Aim 2 could not be credibly evaluated. In contrast the picture task did reliably produce a P300 which varied in relation to accuracy, supporting a portion of hypothesis 1 and confirming findings by de Bruijn (2007) that the P300 responded to error based information. Further, while the picture task did not support hypothesis 3, results offered considerable information related to how P300 data could explain error related findings following M/S TBI. Evaluation of the results raised the possibility of several promising avenues of research to expand understanding of error related changes following M/S TBI.

One such avenue of future research was to explore the contribution of task complexity in increased naturalistic behavior errors following M/S TBI. The results of the picture task showed that individual with M/S TBI deviated from healthy controls in how they processed complex information. Future studies could explore whither TBI related differences in processing complex information were specific to error processing tasks, or if changes are more pervasive across all tasks. It could also be important to replicate the experimental findings in a less chronic sample of individuals with M/S TBI given the tendency of the P300 to change across time since injury.

The results of such an experiment could supply useful information related to rehabilitation and the course of recovery over time.

Information about complexity thresholds could also be important for understanding differences between controls and individuals with M/S TBI. Tasks with stimuli of gradually increasing complexity could help to establish a threshold at which M/S TBI related deviations in error processing appear. In addition, researchers could perform controlled behavioral studies evaluating error rates on tasks of varying complexity to establish a complexity threshold for real world behaviors to verify if task complexity plays an important role in error rates following M/S TBI. While the results of such a study may seem obvious, in combination with neurophysiological studies it could lend support to explaining how neurophysiological findings contribute to error related changes following M/S TBI. Additional research also needs to be conducted to further evaluate the possibility of alternative pathways for processing complex error related information as opposed to simpler information.

Limitations

The current study does have several limitations which limit scientific inference and should be considered. Many of those limitations are related to the participant sample. Primarily that it may have been too small. In addition, individuals with M/S TBI who participated in the current study were unusually remote from time of injury compared to the general body of research. In truth, chronic time since injury could be seen as a positive aspect of the study as it establishes a base for making inferences about long-term behavior change following M/S TBI. Participants were a mean of 9.61 years (SD 7.92, Range 3 – 32) post injury. Comparability of the current study sample to other studies in the literature was limited in regard to the convergent validity because of time since injury. Some similarities in findings were present, such as

decreasing P300 amplitude with increasing injury severity and that task played an important role in how P300 amplitude varied.

A more problematic issue elated to time since injury was that several participants were not able to supply appropriate medical records, and requests to medical centers were not always helpful. Some medical centers were more cooperative than others in supplying appropriate medical information when records were available. In instances were medical records were not available, confirmation of duration of LOC or PTA was obtained from current medical providers or family members. In general the participants who did not provide medical records were significantly impaired and permanently disabled. For three of the six individuals without records included in the picture task the primary investigator was able to speak with a direct medical provider to view neuroimaging and/or confirm LOC and PTA. However, we were unable to obtain the medical records for these individuals.

Lack of salient medical records has several implications for the generalizability and interpretation of study findings. One, it reduces confidence that all study participant met criteria for the study. Reduced confidence in the representative nature of the sample limits what researchers can infer about the meaning of the study findings for the wider population of individuals with M/S TBI. In addition, the lack of neuroimaging data for some participants complicates interpretation of the data. Neuroimaging data is helpful in identifying lesions in participants which might have a direct effect on ERP components. In the case of the P300 medial-temporal lobe injuries (Duncan, Barry, Connolly, Fischer, Michie, Naatanen, et al., 2009) have been found to affect amplitude.

Another concern with the current study sample is that the control group and the TBI group did not significantly differ on a number of objective tests of cognitive functioning.

Surprisingly it was the control group which demonstrated an unusually low group mean on several measures, especially in areas of working memory, learning, and recall. Similar performance on objective measures of cognitive impairment, despite the limited nature of the evaluation, does raise the question of why such similar groups produced divergent results on ERP data.

The most likely reason to explain differences in the sample was based in the idea that differences in P300 amplitude and latency were related to difference in how the groups responded to the tasks complexity. All of the neuropsychological measures given in the study used relatively simple stimuli and thus likely did not evaluate well the executive control elements required in processing complex information. That being said re-evaluation of the study findings using a more diverse sample is recommended.

Another sample-based limitation is that groups differed on measures of depression and anxiety. No studies to data have evaluated the effects of depression on oERN amplitude. Few studies have evaluated the effects of depression and anxiety on P300 amplitude. Results have been inconsistent with some studies finding larger P300 amplitudes in depression (Krompinger & Simons, 2011), some finding decreased amplitude (Ruchsow et al., 2008), and some finding no effect of depression on P300 amplitude (Enoch, White, Waheed, & Goldman, 2008; Kaiser et al., 2003; Quinn, Harris, & Kemp, 2012). Only one article was found evaluating the effect of anxiety on P300 amplitude (Enoch et al., 2008). The results indicated a larger P300 in pure anxiety disorders but no difference in P300 amplitude between controls and individuals with comorbid anxiety disorders. In the current study I did not methodologically control for depression and anxiety in the TBI group. As a result, there is some possibility that ERP amplitudes elicited on the picture task and the observer task were affected by participant mood.

Individuals with M/S TBI endorsed significantly more mood symptoms than controls but a mix of symptom profiles (both anxiety and depression within and between subjects) makes it less likely that the sample characteristic of mood significantly affected ERP amplitudes.

Beyond the sample, another limitation of the current study was that the picture task used to elicit the P300 was a new task created for this dissertation. Additional studies will be needed to verify that the task can reliably produce similar results in other samples. Creation of new tasks is not unusual in the study of ERPs; however, the complexity of the neurological processes involved in the picture task when compared to more common tasks does call for some additional caution. This is well illustrated by the observer task in the current study. The observer task was modeled after previous studies using an Erikson flanker task. Unfortunately, it is likely that changes in the task components (the elimination of short breaks and not counting errors) unexpectedly changed the measure. That being said, a small pilot study using both the picture and the observer tasks had previously demonstrated that the picture and observer tasks functioned as predicted. Verification of the study's results in a different sample is necessary to definitively support a task-based explanation for the lack of findings in the observer task and for confirming the complexity argument to explain findings on the picture task.

A final limitation mentioned here is the lack of behavioral data for confirming adequate participation in the study tasks. Behavioral data typically includes information such as response times or individual error rates on each task. Behavioral data is used in ERP research as a manipulation check to confirm that tasks were accomplished as intended. On tasks that require the participant to observe another's behaviors, avenues for collecting behavioral data are limited. In this study no behavioral data was available on the observer task. On the picture task participants were asked to count the number of error trials presented (de Bruijn & von Rhein,

2012; van Schie et al., 2004). The manipulation check encouraged participants to focus on the task and confirmed that all participants were attending appropriately; however, the intervention did complicate the interpretation of ERP data by adding an additional cognitive task. Nevertheless, interpretation of P300 results would have been even more complicated without the check as there would have been no method of confirming that participants actual engaged in the task. Without some confirmation of task engagement only limited inferences could have been confidently drawn from the study's findings. In addition, since both groups engaged in the manipulation check group difference can still be interpreted as suggesting deviation in the TBI group from control group behavior.

Summary and Conclusions

In this study I found that individuals with M/S TBI demonstrated significant differences in how the responded to the picture task compared to healthy controls on both the amplitude and latency of the P300. Neither the healthy controls nor the individuals with M/S TBI produced a typical oERN during the experiment. The observer task did not work to reliably elicit the oERN in either group. As a result, hypothesis one (that individuals with M/S TBI would produce a measurable oERN) could not be properly evaluated. Hypothesis two (that individuals with M/S TBI would show reduced oERN amplitude on a simple laboratory task) also could not be properly evaluated.

Control group changes on the P300 during the picture task appeared to match previous findings which suggested a difference in context updating processes or cognitive control processes on complex tasks. Individuals with M/S TBI demonstrated no significant change in neurophysiological markers of error processing between error and correct trials. The results suggested a failure by participants with M/S TBI to modify neuronal processes in the presence of

errors and a possible lack of efficiency in categorizing complex information. Result do provide evidence for study Aim 3 (examine the effects of TBI on the amplitude of the P300 as a reflection of cognitive control processes related to error detection and awareness). Results suggested that controls and individuals with M/S TBI differed in how they responded to the picture task on both P300 amplitude and latency. The results suggest the possibility that P300 may index changes in cognitive control on naturalistic action tasks suggesting chronic alterations in the processing of error related information following M/S TBI. That being said, the limitations listed above with the study sample and study tasks, and the lack of significant between group differences in P300 amplitude despite a significant interaction effect make replication of the study results imperative to increase confidence in the findings.

The findings of this experiment do fit well in the context of previous research on the P300 despite the contrast with de Bruijn et al. (2007), and have helped to generate several promising avenues of future research related to neurological processing of errors following M/S TBI. Research to expand on these finding could focus on isolating components of the P300 (e.g., P3a or P3b) to evaluate if they are differentially involved in observed differences. Studies could further explore the possibility of a dual error processing systems. More research could be initiated as well to explore a threshold of complexity for the observed findings in the current study.

In conclusion, a difficulty with the identification of personal errors and a failure to correct those errors continues to be a problem for individuals with M/S TBI. This study is the first to evaluate the possibility that recording ERPs during the observation of more naturalistic errors could be useful in providing additional understanding of functional deficits seen following M/S TBI. Continued research into how individuals understand and identify errors in everyday

behavior will eventually allow clinicians to more successfully target deficits in their efforts at rehabilitation.

References

Allain, S., Carbonnell, L., Falkenstein, M., Burle, B., & Vidal, F. (2004). The modulation of the Ne-like wave on correct trials foreshadows errors. *Neuroscience Letters, 372*, 161-166.

Allport, A. (1987). Selection for action: Some behaviorial and neurophysiological considerations of attention and action. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on perception and action.* (pp. 395-419). Hillsdale, NJ England: Lawrence Erlbaum Associates, Inc.

Bartholow, B. D., Pearson, M. A., Dickter, C. L., Sher, K. J., Fabiani, M., & Gratton, G. (2005). Strategic control and medial frontal negativity: Beyond errors and response conflict. *Psychophysiology, 42*(1), 33-42. doi: 10.1111/j.1469-8986.2005.00258.x

Bashore, T. R., & Ridderinkhof, K. R. (2002). Older age, traumatic brain injury, and cognitive slowing: Some convergent and divergent findings. *Psychological Bulletin, 128*(1), 151-198. doi: 10.1037/0033-2909.128.1.151

Bates, A. T., Patel, T. P., & Liddle, P. F. (2005). External behavior monitoring mirrors internal behavior monitoring. *Journal of Psychophysiology, 19*(4), 281-288. doi: 10.1027/0269-8803.19.4.281

Bendlin, B. B., Ries, M. L., Lazar, M., Alexander, A. L., Dempsey, R. J., Rowley, H. A., . . . Johnson, S. C. (2008). Longitudinal changes in patients with traumatic brain injury assessed with diffusion-tensor and volumetric imaging. *NeuroImage, 42*(2), 503-514. doi: 10.1016/j.neuroimage.2008.04.254

Benton, A. L. (1994). Neuropsychological assessment. *Annual Review of Neuropsychology, 45*, 1-23.

Bigler, E. D. (2005). Structural imaging. In J. M. Silver & S. C. Yudofsky (Eds.), *Textbook of Traumatic Brain Injury* (pp. 87). Washington DC: American Psychiatric Press.

Bigler, E. D. (2007). Anterior and middle cranial fossa in traumatic brain injury: Relevant neuroanatomy and neuropathology in the study of neuropsychological outcome. *Neuropsychology, 21*(5), 515-531. doi: 10.1037/0894-4105.21.5.515

Bjelland, I., Dahl, A. A., Haug, T. T., & Neckelmann, D. (2002). The validity of the Hospital Anxiety and Depression Scale: An updated literature review. *Journal of Psychosomatic Research, 52*(2), 69-77.

Blakemore, S.-J., & Robbins, T. W. (2012). Decision-making in the adolescent brain. *Nature and Neuroscience, 15*(9), 1184-1191.

Botvinick, M. M., Carter, C. S., Braver, T. S., Barch, D. M., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*, 624-652.

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: An update. *Trends in Cognitive Sciences, 8*(12), 539-546. doi: 10.1016/j.tics.2004.10.003

Botwinick, J., Storandt, M., Berg, L., & Boland, S. (1988). Senile dementia of the Alzheimer's type: Subject attrition and testability in research. *Archives of Neurology, 45*, 493-496.

Brazil, I. A., de Bruijn, E. R. A., Bulten, B. H., von Borries, A. K. L., van Lankveld, J. J. D. M., Buitelaar, J. K., & Verkes, R. J. (2009). Early and late components of error monitoring in violent offenders with psychopathy. *Biological Psychiatry, 65*(2), 137-143. doi: 10.1016/j.biopsych.2008.08.011

Buchanan, R. W., Strauss, M. E., Kirkpatrick, C. H., Breier, A., & Carpenter, J. (1994). Neuropsychological impairments in deficit and non-deficit forms of schizophrenia. *Archives of General Psychiatry, 51*, 801-811.

Butters, M. A., Kaszniak, A. W., Glisky, E. L., Eslinger, P. J., & Schachter, D. L. (1994). Recency discrimination deficits in frontal lobe patients. *Neuropsychology, 8*, 343-353.

Buxbaum, L. J., Schwartz, M. F., & Montgomery, M. W. (1998). Ideational apraxia and naturalistic action. *Cognitive Neuropsychology, 15*(6), 617-643.

Carp, J., Halenar, M. J., Quandt, L. C., Sklar, A., & Compton, R. J. (2009). Perceived similarity and neural mirroring: Evidence from vicarious error processing. *Social Neuroscience, 4*(1), 85-96. doi: 10.1080/17470910802083167

Carter, C. S., Braver, T. S., Barch, D. M., Botvinick, M., Ross, L. L., Stenger, V. A., Cohen, J. D. (1998). Anterior cingulate cortex, error detection, and the online monitoring of performance. *Science, 280*, 747-749.

Carter, C. S., MacDonald, A. M., Botvinick, M., Ross, L. L., Stenger, V. A., Noll, D., & Cohen, J. D. (2000). Parsing executive processes: Strategic vs. evaluative functions of the anterior cingulate cortex. *Proceedings Of The National Academy Of Sciences Of The United States Of America, 97*(4), 1944-1948.

Clayson, P. E., Baldwin, S. A., & Larson, M. J. (2013). How does noise affect amplitude and latency measurement of event-related potentials (ERPs)? A methodological critique and simulation study. *Psychophysiology, 50*(2), 174-186. doi: 10.1111/psyp.12001

Cohen, A. S., Pfister, B. J., Schwarzbach, E., Sean Grady, M., Goforth, P. B., & Satin, L. S. (2007). Injury-induced alterations in CNS electrophysiology. In T. W. John & I. R. M. Andrew (Eds.), *Progress in Brain Research* (Vol. 161, pp. 143-169): Elsevier.

Cohen, J., & Polich, J. (1997). On the number of trials needed for P300. *International Journal of Psychophysiology, 25*(3), 249-255. doi: http://dx.doi.org/10.1016/S0167-8760(96)00743-X

Coles, M. G. H., Scheffer, M. K., & Holroyd, C. B. (2001). Why is there an ERN/Ne on correct trials? Response representations, stimulus-related components, and the theory of error-processing. *Biological Psychology, 56*, 173-189.

Cook, L. G., Chapman, S. B., & Levin, H. S. (2008). Self-regulation abilities in children with severe traumatic brain injury: A preliminary investigation of naturalistic action. *NeuroRehabilitation, 23*(6), 467-475.

Cremona-Meteyard, S. L., & Geffen, G. M. (1994). Event-related potential indices of visual attention following moderate to severe closed head injury. *Brain Injury, 8*(6), 541-558. doi: doi:10.3109/02699059409151006

Dale, A. M., & Halgren, E. (2001). Spatiotemporal mapping of brain activity by integration of multiple imaging modalities. *Current Opinion in Neurobiology, 11*(2), 202-208.

Davies, P. L., Segalowitz, S. J., & Gavin, W. J. (2004). Development of response-monitoring ERP's in 7 to 25 year olds. *Developmental Neuropsychology, 25*(3), 355-376.

de Bruijn, E. R. A., Schubotz, R. I., & Ullsperger, M. (2007). An event-related potential study on the observation of erroneous everyday actions. . *Cognitive, Affective, & Behavioral Neuroscience, 7*(4), 278-285.

de Bruijn, E. R. A., & von Rhein, D. T. (2012). Is your error my concern? An event-related potential study on own and observed error detection in cooperation and competition. [Original Research]. *Frontiers in Neuroscience, 6*. doi: 10.3389/fnins.2012.00008

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analsis. *Journal of Neuroscience Methods, 134*, 9-21.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18*(1), 193-222. doi: doi:10.1146/annurev.ne.18.030195.001205

Dien, J., Michelson, C. A., & Franklin, M. S. (2010). Separating the visual sentence N400 effect from the P400 sequential expectancy effect: Cognitive and neuroanatomical implications. *Brain Research, 1355*, 126-140. doi: 10.1016/j.brainres.2010.07.099

Dien, J., Spencer, K. M., & Donchin, E. (2004). Parsing the late positive complex: Mental chronometry and the ERP components that inhabit the neighborhood of the P300. *Psychophysiology, 41*(5), 665-678. doi: 10.1111/j.1469-8986.2004.00193.x

Duncan-Johnson, C. C., & Donchin, E. (1977). On quantifying surprise: The variation of event-related potentials with subjective probability. *Psychophysiology, 14*, 456–467.

Duncan-Johnson, C. C., & Donchin, E. (1982). The P300 component of the event-related brain potential as an index of information processing. *Biological Psychology, 14*(1-2), 1-52. doi: 10.1016/0301-0511(82)90016-3

Duncan, C. C., Barry, R. J., Connolly, J. F., Fischer, C., Michie, P. T., Näätänen, R., . . . Van Petten, C. (2009). Event-related potentials in clinical research: Guidelines for eliciting, recording, and quantifying mismatch negativity, P300, and N400. *Clinical Neurophysiology, 120*(11), 1883-1908. doi: 10.1016/j.clinph.2009.07.045

Duncan, C. C., Kosmidis, M. H., & Mirsky, A. F. (2003). Event–related potential assessment of information processing after closed head injury. *Psychophysiology, 40*(1), 45-59. doi: 10.1111/1469-8986.00006

Duncan, C. C., Summers, A. C., Perla, E. J., Coburn, K. L., & Mirsky, A. F. (2011). Evalaution of traumatic brain injury: Brain potentials in diagnosis, function, and prognosis. *International Journal of Psychophysiology, 82*, 24-40.

Enoch, M.A., White, K. V., Waheed, J., & Goldman, D. (2008). Neurophysiological and genetic distinctions between pure and comorbid anxiety disorders. *Depression and Anxiety, 25*(5), 383-392. doi: 10.1002/da.20378

Fabiani, M., Gratton, G., & Federmeier, K. D. (2007). Event-related brain potentials: Methods, theory, and applications. In J. T. Cacioppo, L. G. Tassinary & G. G. Berntson (Eds.),

Handbook of Psychophysiology (Third ed., pp. 85-119). New York, New York: Cambridge University Press.

Falkenstein, M., Hohnsbein, J., Hoormann, J., & Banke, L. (1991). Effects of crossmodal divided attention on late ERP components. II. Error processing in choice reaction tasks. *Electroencephalography and Clinical Neurophysiology, 78*, 447-455.

Fleming, S. M., & Dolan, R. J. (2012). The neural basis of metacognitive ability. *Philosophical Transactions of the Royal Society B: Biological Sciences, 367*(1594), 1338-1349. doi: 10.1098/rstb.2011.0417

Freeman, W. J., Ahlfors, S. P., & Menon, V. (2009). Combining fMRI with EEG and MEG in order to relate patterns of brain activity to cognition. *International Journal of Psychophysiology, 73*(1), 43-52.

Gean, A. D. (1994). *Imaging of head trauma* (pp. 107-124). New York: Raven Press.

Gehring, W. J., Goss, B., Coles, M. G. H., Meyer, D. E., & Donchin, E. (1993). A neural system for error detection and compensation. *Psychological Science, 4*, 385-390.

Gemba, H., Sasaki, K., & Brooks, V. B. (1986). 'Error' potentials in limbic cortex (anterior cingulate area 24) of monkeys during motor learning. *Neuroscience Letters, 70*, 223-227.

Gladsjo, J. A., Schuman, C. C., Evans, J. D., Peavy, G. M., Miller, S. W., & Heaton, R. K. (1999). *Norms for letter and category fluency: Demographics corrections for age, education, and ethnicity.* Odessa, FL: PAR.

Gloor, P. (1969). Hans Berger and the discovery of the electroencephalogram. Introduction to Hans Berger on the electroencephalogram of man. The fourteen original reports, translated and edicted by P.Gloor. *Electroencephalogram Clinical Neurophsysiology, 28*, 1-36.

Grace, J., & Malloy, P. F. (2001). *Frontal Systems Behavior Scale Professional Manual*. Lutz, FL: Psychological Assessment Resources, Inc.

Hajcak, G., MacNamara, A., & Olvet, D. M. (2010). Event-related potentials, emotion, and emotion regulation: An integrative review. *Developmental Neuropsychology, 35*(2), 120-155.

Hajcak, G., McDonald, N., & Simons, R. F. (2003). Anxiety and error-related brain activity. *Biological Psychology, 64*(1), 77-90.

Hannay, H. J., Howieson, D. B., Loring, D. W., Fisher, J. S., & Lezak, M. D. (2004). Neuropathology for neuropsychologists. In M. D. Lezak, D. B. Howieson & D. W. Loring (Eds.), *Neuropsychological Assessment* (Fourth Edition, pp. 157-285). New York, New York: Oxford University Press.

Hart, T., Giovannetti, T., Montgomery, M. W., & Schwartz, M. F. (1998). Awareness of errors in naturalistic action after traumatic brain injury. *The Journal of Head Trauma Rehabilitation, 13*(5), 16-28.

Hillyard, S. A., Hink, R. F., Schwent, V. L., & Picton, T. W. (1973). Electrical signs of selective attention in the human brain. *Science, 182*(177–80).

Hoenig, J. M., & Heisey, D. M. (2001). The abuse of power: The pervasive fallacy of power calculations for data analysis. *The American Statistician, 55*, 19-24.

Holmes, A. J., & Pizzagalli, D. A. (2008). Spatiotemporal dynamics of error processing dysfunctions in major depressive disorder. *Archives of General Psychiatry, 65*(2), 179-188.

Holroyd, C. B., & Coles, M. G. H. (2002). The neural basis of human error processing: Reinforcement learning, dopamine, and the error-related negativity. *Psychological Review, 109*, 679-709.

Johnson, R., & Donchin, E. (1980). P300 and stimulus categorization: Two plus one is not so different from one plus one. *Psychophysiology, 17*(2), 167-178. doi: 10.1111/j.1469-8986.1980.tb00131.x

Johnstone, B., Callahan, C. D., Kapila, C. J., & Bouman, D. E. (1996). The comparability of the WRAT-R reading test and the NAART as estimates of premorbid intelligence in neurologically impaired patients. *Archives of Clinical Neuropsychology, 11*(6), 513-519.

Jung, M. A., Kim, H. J., Kang, Y. J., & Kim, Y. J. (2013). Development of a modified naturalistic action test for Korean patients with impaired cognition. *Annals of Rehabilitation Medicine, 37*(1), 57-65.

Kaiser, S., Unger, J., Kiefer, M., Markela, J., Mundt, C., & Weisbrod, M. (2003). Executive control deficit in depression: Event-related potentials in a Go/Nogo task. [Article]. *Psychiatry Research-Neuroimaging, 122*(3), 169-184. doi: 10.1016/s0925-4927(03)00004-0

Kasai, T., & Takeya, R. (2012). Time course of spatial and feature selective attention for partly-occluded objects. *Neuropsychologia, 50*(9), 2281-2289. doi: http://dx.doi.org/10.1016/j.neuropsychologia.2012.05.032

Keil, A., Bradley, M. M., Hauk, O., Rockstroh, B., Elbert, T., & Lang, P. J. (2002). Large-scale neural correlates of affective picture processing. *Psychophysiology, 39*(641–9).

Kerns, J. G., Cohen, J. D., MacDonald, A. W, Cho, R. Y., Stenger, V. A., & Carter, C. S. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science, 303*(5660), 1023-1026. doi: 10.1126/science.1089910

Kirschstein, T., & Kohling, R. (2009). What is the source of EEG? *Clinical EEG Neuroscience, 40*(3), 146-149.

Knight, R. T. (1984). Decreased response to novel stimuli after prefrontal lesions in man. *Electroencephalography and Clinical Neurophysiology, 59*, 9-20.

Koban, L., Pourtois, G., Vocat, R., & Vuilleumier, P. (2010). When your errors make me lose or win: Event-related potentials to observed errors of cooperators and competitors. *Social Neuroscience, 5*(4), 360-374.

Kraus, M. F., Susmaras, T., Caughlin, B. P., Walker, C. J., Sweeney, J. A., & Little, D. M. (2007). White matter integrity and cognition in chronic traumatic brain injury: A diffusion tensor imaging study. *Brain, 130*, 2608-2619.

Krompinger, J. W., & Simons, R. F. (2011). Cognitive inefficiency in depressive undergraduates: Stroop processing and ERPs. *Biological Psychology, 86*(3), 239-246. doi: http://dx.doi.org/10.1016/j.biopsycho.2010.12.004

Kutas, M., & Dale, A. (1997). Electrical and magnetic readings of mental functions. In M. D. Rugg (Ed.), *Cognitive Neuroscience* (pp. 197-242). Hove East Sussex, UK: Psychology Press.

Lachapelle, J., Bolduc-Teasdale, J., Ptito, A., & McKerral, M. (2008). Deficits in complex visual information processing after mild TBI: Electrophysiological markers and vocational outcome prognosis. *Brain Injury, 22*(3), 265-274.

Larson, M. J., Baldwin, S. A., Good, D. A., & Fair, J. E. (2010). Brief Reports: Temporal stability of the error-related negativity (ERN) and post-error positivity (Pe): The role of number of trials. *Psychophysiology, 47*(6), 1167-1171. doi: 10.1111/j.1469-8986.2010.01022.x

Larson, M. J., & Clayson, P. E. (2011). The relationship between cognitive performance and electrophysiological indices of conflict- and performance-monitoring. *Cognitive Affective and Behavioral Neuroscience, 11*(2), 159-171.

Larson, M. J., Kaufman, D. A. S., Schmalfuss, I. M., & Perlstein, W. M. (2007). Performance monitoring, error processing, and evaluative control following severe TBI. *Journal of the International Neuropsychological Society, 13*(6), 961-971. doi: 10.1017/s1355617707071305

Larson, M. J., Kaufman, K. A. S., Schmalfuss, I. M., & Perlstein, W. M. (2007). Performance monitoring, error processing, and evaluative control following severe TBI. *Journal of the International Neuropsychological Society, 13*, 961-971.

Larson, M. J., Kelly, K. G., Stigge-Kaufman, D. A., Schmalfuss, I. M., & Perlstein, W. M. (2007). Reward context sensitivity impairement following severe TBI: An event-related potential investigation. *Journal of the International Neuropsychological Society, 13*, 615-625.

Larson, M. J., & Perlstein, W. M. (2009). Awareness of deficits and error processing after traumatic brain injury. *Neuroreport, 20*(16), 1486-1490.

Larson, M. J., Perlstein, W. M., Stigge-Kaufman, D. A., Kelly, K. G., & Dotson, V. M. (2006). Affective context-induced modulation of the error-related negativity. *Neuroreport, 17*, 329-333.

Lew, H. L., Lee, E. H., Pan, S. S. L., & Date, E. S. (2004). Electrophysiologic abnormalities of auditory and visual information processing in patients with traumatic brain injury. *American Journal of Physical Medicine & Rehabilitation, 86*(6), 428-433.

Lew, H. L., Thomander, D., Gray, M., & Poole, J. H. (2007). The effects of increasing stimulus complexity in event-related potentials and reaction time testing: clinical applications in evaluating patients with traumatic brain injury. *Journal of Clinical Neurophysiology, 24*(5), 398-404.

Lezak, M. D. (1995). *Neuropsychological assessment* (3rd Edition, pp. 650-685). New York: Oxford University Press.

Løvstad, M., Funderud, I., Endestad, T., Due-Tønnessen, P., Meling, T. R., Lindgren, M., . . . Solbakk, A. K. (2012). Executive functions after orbital or lateral prefrontal lesions: Neuropsychological profiles and self-reported executive functions in everyday living. *Brain Injury, 26*(13-14), 1586-1598. doi:10.3109/02699052.2012.698787

Lucas, J. A., & Addeo, R. (2006). Traumatic brain injury and post concussion syndrome. In P. J. Snyder, P. D. Nassbaum & D. L. Robins (Eds.), *Clinical Neuropsychology: A pocket Handbook for Assessment* (Second Edition, pp. 351-380). Washington DC: American Psychological Association.

Luck, S. J. (2005). *An introduction to the event-related potential technique*. Cambridge, MA: The MIT Press.

Luu, P., Collins, P., & Tucker, D. M. (2000). Mood, personality, and self-monitoring: Negative affect and emotionality in relation to frontal lobe mechanisms of error monitoring. *Journal of Experimental Psychology: General, 129*, 43-60.

Makeig, S., Westerfield, M., Townsend, J., Jung, T.-P., Courchesne, E., & Sejnowski, T. J. (1999). Functionally independent components of early event-related potentials in a visual spatial attention task. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 354*(1387), 1135-1144. doi: 10.1098/rstb.1999.0469

Menon, R. S., Gati, J. S., Goodyear, B. G., Luknowsky, D. C., & Thomas, C. G. (1998). Spatial and temporal resolution of functional magnetic resonance imaging. *Biochemistry and Cell Biology, 76*(2-3), 560-571.

Menon, V., Adleman, N. E., White, C. D., Glover, G. H., & Reiss, A. L. (2001). Error-related brain activation during a Go/Nogo response inhibition task. *Human Brain Mapping, 12*, 131-143.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24*, 167-202. doi: 10.1146/annurev.neuro.24.1.167

Miltner, W. H. R., Brauer, J., Hecht, H., Trippe, R., & Coles, M. G. H. (2004). *Parallel brain activity for self-generated and observed errors*. Paper presented at the Current opinions on performance monitoring, Dortmund, Germany, on July 3–5, 2003.

Muñoz-Ruata, J., Caro-Martínez, E., Martínez Pérez, L., & Borja, M. (2010). Visual perception and frontal lobe in intellectual disabilities: A study with evoked potentials and neuropsychology. *Journal of Intellectual Disability Research*, *54*(12) 1116-1129. doi: 10.1111/j.1365-2788.2010.01341.x

Nieuwenhuis, S., Ridderinkhof, K. R., Talsma, D., Coles, M. G. H., Holroyd, C. B., Kok, A., & al., e. (2002). A computational account of altered error processing in older age: Dopamine and the error-related negativity. *Cognitive, Affective, & Behavioral Neuroscience, 2*(1), 19-36.

Olvet, D. M., & Hajcak, G. (2009). The stability of error-related brain activity with increasing trials. *Psychophysiology, 46*(5), 957-961. doi: 10.1111/j.1469-8986.2009.00848.x

Otten, L. J., & Rugg, M. D. (2005). Interpreting event-related brain potentials. In T. C. Handy (Ed.), *Event-Related Potentials: A Methods Handbook* (pp. 3-16). Cambridge, MA: The MIT Press.

Overbeek, T. J. M., Nieuwenhuis, S., & Ridderinkhof, K. R. (2005). Dissociable components of error processing: On the functional significance of the Pe vis-a-vis the ERN/Ne. *Journal of Psychophysiology, 19*(4), 319-329.

Pfefferbaum, A., Ford, J. M., Wenegreat, B. G., Roth, W. T., & Kopell, B. S. (1984). Clinical application of the P3 component of event-related potentials. I. Normal aging. *Electroencephalogram Clinical Neurophysiology, 59*(2), 85-103.

Pfefferbaum, A., Sullivan, E. V., Hedehus, M., Adalsteinsson, E., Lim, K. O., & Moseley, M. (2000). In vivo detection and functional correlates of white matter microstructural disruption in chronic alcoholism. *Alcoholism, clinical and experimental research, 24*(8), 1214-1221.

Polich, J. (2007). Updating p300: An integrative theory of P3a and P3b. *Clinical Neurophysiology, 118*(10), 2128-2148.

Polich, J. (2010). Neuropsychology of P300. In S. J. Luck & E. S. Kappenman (Eds.), *The Oxford handbook of event-related potential components* (pp. 159-188). New York, New York: Oxford University Press, Inc.

Polich, J., & Comerchero, M. D. (2003). P3a from visual stimuli: Typicality, task, and topography. *Brain Topography, 15*(3), 141-152. doi: 10.1023/a:1022637732495

Polich, J., & Criado, J. R. (2006). Neuropsychology and neuropharmacology of P3a and P3b. *International Journal of Psychophysiology, 60*(2), 172-185. doi: http://dx.doi.org/10.1016/j.ijpsycho.2005.12.012

Potter, D. D., Basset, M. R., Jory, S. H., & Barret, K. (2001). Changes in event-related potentials in a three-stimulus auditory oddball task after mild head injury. *Neuropsychologia, 39*(1464-1472).

Quinn, C. R., Harris, A., & Kemp, A. H. (2012). The impact of depression heterogeneity on inhibitory control. *Australian and New Zealand Journal of Psychiatry, 46*(4), 374-383. doi: 10.1177/0004867411432073

Rao, V., & Lyketsos, C. (2000). Neuropsychiatric sequele of traumatic brain injury. *Psychosomatics, 41*, 95-103.

Rey, A. (1958). *L'examen clinique en psychologie.* Paris: Presse Universitaire de France.

Rosburg, T., Boutros, N. N., & Ford, J. M. (2008). Reduced auditory evoked potential component N100 in schizophrenia -- A critical review. *Psychiatry Research, 161*(3), 259-274. doi: DOI: 10.1016/j.psychres.2008.03.017

Ruchsow, M., Groen, G., Kiefer, M., Beschoner, P., Hermle, L., Ebert, D., & Falkenstein, M. (2008). Electrophysiological evidence for reduced inhibitory control in depressed patients in partial remission: A Go/Nogo study. [Article]. *International Journal of Psychophysiology, 68*(3), 209-218. doi: 10.1016/j.ijpsycho.2008.01.010

Ruff, R. M., Light, R. H., Parker, S. B., & Levin, H. S. (1996). Benton controlled oral word association test reliability and updated norms. *Archives of Clinical Neuropsychology, 11*(4), 329-338.

Rutgers, D. R., Toulgoat, F., Cazejust, J., Fillard, P., Lasjaunias, P., & Ducreux, D. (2008). White matter abnormalities in mild traumatic brain injury: A diffusion tensor imaging study. *American Journal of Neuroradiology, 29*(3), 514-519.

Santesso, D. L., & Segalowitz, S. J. (2009). The error-related negativity is related to risk taking and empathy in young men. *Psychophysiology, 46*, 143-152.

Schönberger, M., & Ponsford, J. (2010). The factor structure of the Hospital Anxiety and Depression Scale in individuals with traumatic brain injury. *Psychiatry Research, 179*(3), 342-349. doi: http://dx.doi.org/10.1016/j.psychres.2009.07.003

Schwartz, M. F., Montgomery, M. W., Buxbaum, L. J., Lee, S. S., Carew, T. G., Coslett, H. B., . . . Mayer, N. (1998). Naturalistic action impairment in closed head injury. *Neuropsychology, 12*(1), 13-28.

Segalowitz, S. J., & Dywan, J. (2009). Individual differences and developmental change in the ERN response implications for models of ACC function. *Psychological Research, 73*, 857-870.

Spreen, O., & Strauss, E. (1991). *A compendium of neuropsychological tests: Administration, norms, and commentary*. New York: Oxford University Press.

Stamatakis, E. A., Wilson, J. T. L., Hadley, D. M., & Wyper, D. J. (2002). SPECT imaging in head injury interpreted with statistical parametric mapping. *Journal of Nuclear Medicine, 43*(4), 476-483.

Strauss, E., Sherman, E. M. S., & Spreen, O. (2006). *A compendium of neuropsychological tests* (Third Edition). New York, New York: Oxford University Press.

Swick, D. (2005). ERPs in neuropsychological populations. In T. C. Handy (Ed.), *Event-Related Potentials: A Methods Handbook*. Cambridge, MA: The MIT Press.

Swick, D., & Turken, A. U. (2002). Dissociation between conflict detection and error monitoring in the human anterior cingulate cortex. *Proceedings of the National Academy of Sciences, 99*(25), 16354-16359. doi: 10.1073/pnas.252521499

Teasdale, G., & Jennett, B. (1974). Assessment of coma and impaired consciousness: A practical scale. *Lancet, 304*(7872), 81-84.

Uttl, B. (2002). North american adult reading test: Age norms, reliability, and validity. *Journal of Clinical and Experimental Neuropsychology, 24*(8), 1123-1137. doi: 10.1076/jcen.24.8.1123.8375

van Schie, H. T., Mars, R. B., Coles, M. G. H., & Bekkering, H. (2004). Modulation of activity in medial frontal and motor cortices during error observation. *Euroscience, 7*(5), 549-554.

van Veen, V., & Carter, C. S. (2002). The anterior cingulate as a conflict monitor: fMRI and ERP studies. *Physiology and Behavior, 77*, 477-482.

Vidal, F., Hasbroucq, T., Grapperon, J., & Bonnet, M. (2000). Is the 'error negativity' specific to errors. *Biological Psychology, 51*, 109-128.

WAIS-III and WMS-III Technical Manual. (1997). San Antonio, TX: The Psychological Corporation.

Walhovd, K. B., Rosquist, H., & Fjell, A. M. (2008). P300 amplitude age reductions are not caused by latency jitter. *Psychophysiology, 45*(4), 545-553.

Whelan-Goodinson, R., Ponsford, J., & Schönberger, M. (2009). Validity of the Hospital Anxiety and Depression Scale to assess depression and anxiety following traumatic brain injury as compared with the Structured Clinical Interview for DSM-IV. *Journal of Affective Disorders, 114*(1–3), 94-102. doi: http://dx.doi.org/10.1016/j.jad.2008.06.007

Wu, T. C., Wilde, E. A., Bigler, E. D., Yallampalli, R., McCauley, S. R., Troyanskaya, M., Levin, H. S. (2010). Evaluating the relationship between memory functioning and cingulum bundles in acute mild traumatic brain injury using diffusion tensor imaging. *Journal of Neurotrauma, 27*(2), 303-307. doi: doi:10.1089/neu.2009.1110

Yeung, N., Botvinick, M., & Cohen, J. D. (2004). The neural basis of error detection: Conflict monitoring and the error-related negativity. *Psychological Review, 111*, 931-954.

Yeung, N., & Sanfey, A. G. (2004). Independent coding of reward magnitude and valence in the human brain. *Journal of Neuroscience 24*(28), 6258–6264.

Yeung, N., & Cohen, J. D. (2006). The impact of cognitive deficits on conflict monitoring. Predictable dissociations between the error-related negativity and N2. *Psychological Science, 17*, 164-171.

Yeung, N., & Nieuwenhuis, S. (2009). Dissociating response conflict and error likelihood in anterior cingulate cortex. *The Journal of Neuroscience, 29*(46), 14506-14510. doi: 10.1523/jneurosci.3615-09.2009