2015-06-01

# A Controlled Comparison of Errorless and Errorful Learning in Individuals with Moderate-to-Severe Traumatic Brain Injury

Joseph Edward Fair
*Brigham Young University - Provo*

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Joseph Edward Fair

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
Erin D. Bigler
Ramona O. Hopkins
Scott A. Baldwin
Mikle D. South

Department of Psychology

Brigham Young University

June 2015

ABSTRACT

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Joseph Edward Fair
Department of Psychology, BYU
Doctor of Philosophy

The prevalence and sequelae of moderate-to-severe (M/S) traumatic brain injury (TBI) are significant and pervasive problems, and effective rehabilitation techniques are key. Errorless learning is regarded as a useful tool for memory impairments; however, the efficacy of errorless learning in a M/S TBI population is unclear. The primary goal (aim 1) of this study was to evaluate the efficacy of a single session of errorless vs. errorful learning in a group of M/S TBI survivors and matched controls. A secondary goal (aim 2) was to investigate the neural time course of errorless learning in participants with M/S TBI by analyzing the error-related negativity (ERN) component of the scalp-recorded event-related potential (ERP). The ERN is an electrophysiological measure of error processing that is disrupted in M/S TBI survivors. Measures of neuropsychological performance, self- and informant-report of executive functioning, and affect further informed both study aims.

Data from 28 M/S TBI survivors (9 female) and 28 controls (9 female) were analyzed for aim 1, with data from 19 M/S TBI survivors (6 female) and 20 controls (8 female) analyzed for aim 2. There were significant differences between the TBI and control groups with regard to executive, mood, and neuropsychological functioning. Results from aim 1 indicated that TBI participants were slower across learning conditions, while both groups had significantly faster reaction times in the errorless condition. Regarding accuracy, there was not a statistically significant main effect of learning condition ($p = .07$), group ($p = .06$), or Group x Condition x Accuracy interaction ($p = .33$). Indices of memory and executive functioning, and group (TBI, Control) used in regressions predicted accuracy in both learning conditions ($ps < .01$). The memory composite was a significant independent predictor of errorless accuracy.

Results from aim 2 indicated a reliable ERN was present across conditions, although there were no main effects of Condition, Group, or Group x Condition interactions on ERN amplitude or latency ($ps \geq .22$). ERN latency was not predictive of accuracy for either condition ($ps \geq .08$). Group was a significant independent predictor of accuracy in the errorless condition ($p = .05$), but not the errorful condition ($p = .45$). Findings indicate that memory functioning was a better predictor of accuracy than executive functioning or group membership. This suggests that the errorless learning benefit may be specific to memory functioning, rather than other cognitive variables. This conclusion aligns with research reporting that benefits of errorless learning depend upon the severity of memory impairments. Results from ERN analyses are only partially supported by previous research, and further work is needed to clarify the role of neural representations of errorless learning in M/S TBI.

Keywords: cognitive rehabilitation, errorless learning, errorful learning, traumatic brain injury, TBI, error processing, EEG, error related negativity, ERN

# ACKNOWLEDGEMENTS

Michael Larson has been a fantastic mentor to me over many years. Dr. Larson personifies a truly rare excellence, managing to be relentless in his productivity while being consistently cheerful, friendly, and supportive to those around him. Indeed, his exceptional supervision across multiple clinical and research activities has been the recurring highlight of my time at Brigham Young University. I owe him many things, not the least of which is gratitude for his patience and support during all stages of this dissertation. Long after I leave BYU, I will continue to look to Dr. Larson as a bedrock example of how to work and how to mentor others.

Several research assistants and fellow graduate students have facilitated the progression of this project, the most notable of which are Daniel Bjornn and Spencer Liebel. These fine men have played an invaluable role in collecting, managing, and analyzing data, and otherwise being willing assistants and good friends.

Too often behind the scenes in my academic pursuits has always been my dear wife and friend, Joy Rowland Fair. During nearly all of our 11+ years of marriage, I have been a student; burdening her directly and by association with the many stressors that accompany that role. Joy is a true and loyal friend, patiently supporting me and enduring these many years of difficulty and inconvenience. I am forever in Joy's debt for the saving grace she is in my life. In addition, I offer a sincere acknowledgment to my five children who have suffered my chronic absence and/or distraction for most or all of their lives. They mean the world to me. I always told myself that getting my Ph.D. would (eventually) facilitate spending more time together as a family. I have come to realize that now, not later, is the best time for the relationships that matter most.

Above all, I freely testify that God's grace has strengthened me during these years of graduate training. He and His Son are real. There have been many circumstances when I was blessed far beyond my own natural capacity in order to fulfill my duties to school, work, family, and religion. I have consistently felt inadequate in each of these domains of responsibility, but I know I could not have achieved this or any other success without the sustaining power of heaven and the miracle of Christ's Atonement.

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Each year in the United States approximately 53,000 people die from complications related to traumatic brain injury (TBI; Coronado et al., 2011) and approximately 80,000 individuals become disabled due to moderate-to-severe (M/S) TBI sequelae (Thurman, Alverson, Dunn, Guerrero, & Sniezek, 1999). An estimated 3.17 million people (1.1% of the United States population) live with long-term TBI-related disability (Zaloshnja, Miller, Langlois, & Selassie, 2008). The degree of life disruption, as well as the resolution of TBI-related deficits, depends on injury severity, injury location(s), individual pre-injury functioning, and affective/personality variables (Lezak, Howieson, Bigler, & Tranel, 2012). The most common deficits in functioning following M/S TBI include problems with sustained and divided attention, memory, working memory, and executive functioning (Strangman et al., 2005). Even five years post-injury, memory, attention, and speed of processing tend to be areas of weakness (Dikmen, Machamer, Powell, & Temkin, 2003; Millis et al., 2001). Long-term physical health problems such as metabolic/endocrine dysfunction, seizures, headaches, sleep disturbance, and incontinence are also reported (Murphy & Carmine, 2012). There is also a decline in quality of life (Dijkers, 2004) and increased risk of later development of Alzheimer's disease and other dementias as a result of M/S TBI (Bigler, 2009; Plassman et al., 2000; Starkstein & Jorge, 2005).

Another common deficit experienced by many TBI survivors is a reduction in cognitive control abilities (Larson, Clayson, & Farrer, 2012; Larson, Farrer, & Clayson, 2011; Larson, Kaufman, Schmalfuss, & Perlstein, 2007; Larson, Perlstein, Stigge-Kaufman, Kelly, & Dotson, 2006; Perlstein et al., 2004; Perlstein, Larson, Dotson, & Kelly, 2006; Scheibel et al., 2007; Scheibel et al., 2003; Sozda, Larson, Kaufman, Schmalfuss, & Perlstein, 2011). Cognitive

control involves the orchestration of thought and action towards the execution of an internal goal and is critical to adaptive goal-directed behaviors (Levine, Katz, Dade, & Black, 2002; Miller & Cohen, 2001). Cooking with a recipe, completing a "to do" list, and following the rules/guidelines of a game or on a job site are all examples of the application of cognitive control. Cognitive control separates both functionally and temporally into regulative and evaluative component processes (Carter et al., 2000; Perlstein et al., 2006).

The regulative component of cognitive control involves internal representations of information that can be used to influence processing and/or responses during a task (Braver, Barch, & Cohen, 1999). For example, regulative control could include maintaining an awareness of game rules or task instructions and using that information to guide decisions (Cohen & Servan-Schreiber, 1992). Survivors of M/S TBI have deficits in this regulative aspect of cognitive control which are related to reports of problems in functioning, particularly in unstructured real-life situations where environmental cues or learned routines may be minimal or absent (Seignourel et al., 2005). These areas of deficit may include problems in child rearing, making major purchases, navigating social situations, or completing occupational tasks (Levine et al., 2002; Lezak et al., 2012). The neural instantiation of the regulative aspect of cognitive control is based primarily in the dorsal-lateral pre-frontal cortex (DLPFC; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004; Wagner, Maril, Bjork, & Schacter, 2001).

Evaluative cognitive control processes include the functions of conflict monitoring and error-related performance monitoring (Botvinick, Carter, Braver, Barch, & Cohen, 2001; Larson, Kaufman, et al., 2007). Examples of evaluative control could include the ability to adjust attention and motivation while completing a task, noticing when mistakes are made, monitoring performance/competition, orienting to novelty, and engaging in complex motor control (Bush,

Luu, & Posner, 2000). The neural bases of evaluative cognitive control processes have been localized to the anterior cingulate cortex (ACC; Bush et al., 2000; van Veen & Carter, 2002a, 2002b).

Error-related performance monitoring is an evaluative-control process that is disrupted in individuals with mild and severe TBI (Larson, Clayson, et al., 2012; Larson, Fair, Farrer, & Perlstein, 2011; Larson, Kaufman, Kellison, Schmalfuss, & Perlstein, 2009; Larson, Kaufman, et al., 2007) and may result in deficits such as poor awareness of mistakes, not adjusting behavior or strategy when mistakes are made, and inadequate recognition of inappropriate social or interpersonal behaviors. Theories and research propose that when the ACC detects errors or that task demands have exceeded present levels of cognitive control (i.e., conflict between competing response options), the ACC signals the regulative processes of the DLPFC, which then implements needed adjustments in performance in order to improve the likelihood of success (Botvinick et al., 2001; Miller & Cohen, 2001). In healthy individuals, the evaluative and regulative processes work together to ensure effective performance and adaptation, but this system is deficient in survivors of M/S TBI (Larson, Kaufman, et al., 2007; Larson, Perlstein, Stigge-Kaufman, et al., 2006; Perlstein et al., 2004; Perlstein et al., 2006; Scheibel et al., 2007; Scheibel et al., 2003). Consequently, the need for restorative and/or compensatory strategies is necessary for improving cognitive functioning and quality of life following M/S TBI.

## Cognitive Rehabilitation Techniques and Errorless Learning

Treatment and rehabilitation of cognitive control and error-related performance monitoring dysfunction following M/S TBI are valuable because these are fundamental aspects of goal-directed behavior and are common areas of dysfunction following M/S TBI. Given the vast array of possible sequelae due to individual differences in injury location and severity

(Lezak et al., 2012), it is important that rehabilitation approaches be individually tailored to each patient, with both the survivor of TBI and their family members involved in treatment goals and the rehabilitation process.

**Cognitive Rehabilitation**

Cognitive rehabilitation generally falls into one of two categories: compensatory strategies and retraining processes (Rohling, Faust, Beverly, & Demakis, 2009). Compensatory behavior is a common tool for dealing with various types of dysfunction, and involves utilizing other non- (or less) impaired abilities to achieve a desired outcome. In the case of M/S TBI, the need for compensation arises when a decrease in skill or ability occurs without a decrease in environmental demand. For example, when a survivor of M/S TBI experiences a diminished capacity to sustain attention and remember tasks at work; something previously done with little or no effort. Thus, the reduced capacities of the injured employee are at odds with the unaltered demands of the workplace. The resulting interaction requires compensation in the form of increased time and effort to complete the task, substitution of similar skills, or the utilization of other cognitive, behavioral, or external resources to accomplish the task (Wilson, 2003).

In contrast to compensatory strategies, retraining methods involve rehabilitating damaged processes in order to improve or restore a particular area of functioning. Sometimes referred to as a "mental muscle" technique, J. M. Williams (1987) recommends that retraining/rehabilitation "should have a goal-attainment focus instead of a symptom-reduction focus," (p. 47) emphasizing the generalization of common tasks to other specific scenarios or goals. This process may be slow, involving extensive repetition, and graduating from simple to more complex tasks (Tsaousides & Gordon, 2009). Whether rehabilitation goals include retraining or compensation, there is evidence that spending more time in intensive, comprehensive

rehabilitation programs results in faster and earlier improvements in functioning (Chua, Ng, Yap, & Bok, 2007). Some researchers estimate that no less than 100 hours of cognitive rehabilitation will achieve strong results (see Chua et al., 2007; Prigatano, 1999), while others have found over 300 hours to be most beneficial (Leon-Carrion, Dominguez-Morales, Barroso y Martin, & Leon-Dominguez, 2012).

In addition to retraining and compensatory strategies, Prigatano (2008) suggests a third area of rehabilitation, one that includes "patients' subjective experience of their losses…and how it influences what happens in rehabilitation" (p. 985). The typical brain injury survivor inevitably faces the issue of appraisal; that is, how they react to the events and sequelae of their injury. If negative appraisals characterize their reactions to deficits, anxiety and/or depression (negative affect) may result. Indeed, in survivors of M/S TBI, depression and anxiety symptoms frequently co-occur (Jorge et al., 2004), and are the most common emotional sequelae (Silver, Kramer, Greenwald, & Weissman, 2001). These negative appraisals and emotions are important to be included in rehabilitation interventions, as negative affect-related changes in cerebral function are associated with deficits in memory, attention, decreased motor functions, and impaired executive functioning (Emerson, Harrison, Everhart, & Williamson, 2001; Emerson, Mollet, & Harrison, 2005; Mialet, Pope, & Yurgelun-Todd, 1996; Shenal, Harrison, & Demaree, 2003; Sweeney, Kmiec, & Kupfer, 2000; Trichard et al., 1995).

**Errorless learning.** Error-related performance monitoring and memory deficits are among the more common symptoms of M/S TBI (Lezak et al., 2012) and errorless learning is a cognitive rehabilitation strategy employed to improve the encoding and subsequent retention of information. Originally developed in the 1960's, errorless learning was first applied to the treatment of memory problems by Wilson, Baddeley, and Evans (1994) who found that it was

superior to errorful (i.e., trial and error) learning. Baddeley and Wilson (1994) proposed that errorless learning both improves learning and reduces frequency of forgetting. Central to the errorless learning technique is that the individual is prevented from making errors while learning the task, and thus from having potentially conflicting memories interfere with learning and/or retrieving target information.

What follows is an example of a possible errorless learning task, and the general steps that may occur during a session of errorful and errorless learning. If a client's goal is to remember a word, one approach could be to view or hear the first three letters of the word they are to remember and then hear from the therapist what the word is without mention of other "non-target" words. In errorful learning (sometimes called trial-and-error learning), an individual sees the first three letters of a word and guesses what the word might be. After 2-3 guesses, the therapist tells what the word is, and asks the client to remember it. Thus, with errorless learning the target word is stated and additional non-target words are not introduced during the initial introduction phase (unlike errorful learning), increasing the probability that the target word will be correctly retrieved and/or recognized later because alternate words that serve as a distraction are not encoded or recalled. The client then recalls the previously learned target words during subsequent recall, cued recall, or recognition phases.

Elaborations on errorless learning, specifically, self-generation, have shown to increase the efficacy of the technique in clinical and non-clinical populations. More specifically, Tailby and Haslam (2003) provided clients with an opportunity to produce the target word themselves rather being told the word to remember. They were given a verbal description such as, "I'm thinking of a five-letter word beginning with 'BR', and this word describes a food made of flour, liquid and yeast which is baked and then sliced to make sandwiches. What do you think the

word might be?" (p. 1235). Comparing self-generated errorless learning with traditional errorless learning revealed the self-generated errorless method was superior (2003). Tailby and Haslam concluded that using the self-generated errorless learning method not only improves retention/processing but also encourages client participation in the rehabilitation process. Along these lines, Lubinsky, Rich, and Anderson (2009) reported that, in older adults with amnestic MCI, self-generation enhanced the errorless learning benefit in cued recall. Guild and Anderson (2012) further explored these findings in healthy older adults and found that self-generation enhanced errorless learning in free recall as well. When considered together, the extant research suggests that self-generation is an effective addition to the errorless learning technique and may increase rehabilitative gains in clinical populations.

Another example of the application of errorless learning is the method of vanishing cues. Vanishing cues involves providing a name or a list to remember, and for each correctly remembered trial, a letter is removed from the end of the word or list. Letters vanish with each successful trial unless the client makes a mistake, at which point the process starts over. This technique decreases the probability of non-target information interfering with later recollection. There is less support for the carryover of vanishing cues to other contexts (Glisky, 1995), and evidence suggests that combining vanishing cues and errorless learning is no more effective than errorless learning alone (Haslam, Moss, & Hodder, 2010). Taken together, errorless learning has "real-world" potential because remembering simple instructions, addresses, phone numbers, names of doctors, relatives, or friends are better acquired and retained using this method (Evans et al., 2000; Pitel et al., 2006).

**Errorless learning and clinical populations.** There are several studies regarding the use/application of errorless learning in adults with various cognitive impairments from a variety

of causes. For example, Kessels and de Haan (2003) conducted a meta-analysis of errorless and/or vanishing cues studies and found 27 articles between 1986 and 2002. After excluding studies that lacked control groups or were of single cases eight errorless learning studies were included in the final analyses (with three using vanishing cues). A large effect size of 0.87 emerged when comparing errorless to errorful conditions, with an effect size of 0.27 for vanishing cues methods. These results indicate errorless learning is superior to errorful and vanishing cues methods of cognitive rehabilitation with amnestic clients.

Since the Kessels and de Haan (2003) meta-analysis, errorless learning research continued with several different clinical populations. Not including case studies, research has included adults with dementia (de Werd, Boelen, Rikkert, & Kessels, 2013; Dechamps et al., 2011; Kessels & Hensken, 2009), mild cognitive impairment (Akhtar, Moulin, & Bowie, 2006; Lubinsky et al., 2009), children with amnesia and acquired brain injury (ABI; Guillery-Girard, Martins, Parisot-Carbuccia, & Eustache, 2004; Haslam, Bazen-Peters, & Wright, 2012), and one functional magnetic resonance imaging (fMRI) study involving 13 individuals with diffuse axonal injury (DAI; Ueno et al., 2009). Each of these studies found errorless learning to be of greater benefit than other default learning methods such as errorful learning.

One additional study with an adequate sample size examined the effects of errorless learning following TBI, although they did not have a healthy control group. Lloyd, Riley, and Powell (2009) tested 20 individuals with acquired brain injury (e.g. including TBI, vascular disorders, and cysts) using errorless learning to learn a route through a virtual reality town. Each participant learned two routes (an errorful and errorless route) and the errorless condition resulted in the commission of significantly fewer errors when compared to errorful learning. In another study, a computerized version of errorless learning given to 18 TBI patients revealed that

computer administered sessions were just as effective as therapist administration, if not more so (Dou, Man, Ou, Zheng, & Tam, 2006). However, the aim of this study was to compare methods of administration of errorless learning and did not have an errorful condition or a healthy non-injured control group.

Despite its reported efficacy, a thorough review of the errorless learning literature reveals that it may be a more effective cognitive rehabilitation tool for some populations and tasks than others. And some have cautioned that errorless learning "can only be applied in well-described and straightforward tasks and no transfer to other tasks is expected" (Kessels & Hensken, 2009, p. 311). Findings contrary to the efficacy of errorless learning are reported by Mount et al. (2007) who taught functional/behavioral tasks (preparing a wheelchair for transfer, and putting on a sock with a sock-donner) to victims of stroke (n = 33) and found that errorless learning was no more effective than errorful learning. Furthermore, for the sock-donning task, trial and error (i.e., errorful) had greater carryover effect- or was more effective in transferring skills to another similar undertaking. Similarly, results are at present contradictory regarding the effectiveness of errorless tasks for learning a procedural task such as programming an electronic organizer or using a word processor (Evans et al., 2000; Pitel et al., 2006; Wilson et al., 1994). Noonan, Pryer, Jones, Burns, and Lambon Ralph (2012) compared errorless and errorful therapies in an Alzheimer's disease population (n = 8) and found that they were equally effective, on both an individual and group level, for treating anomia. Ruis and Kessels (2005) tested face-name associations with 10 Alzheimer's patients and found no benefit between errorless and errorful conditions following a 10 minute delay. Another study using children with TBI did not support the general use of errorless learning given that injury severity, age, retention duration, or learning modality did not consistently favor errorless learning over trial and error (Landis et al., 2006).

Although the research published to date is valuable, there are no studies utilizing samples of adults with M/S TBI that compares the efficacy of errorless and errorful learning within participants as well as between groups (i.e., TBI and control). Errorless learning is a cognitive rehabilitation method that often works, but more information is needed to clarify for which populations and what tasks are best suited for its use. Furthermore, the neural mechanisms underlying the rehabilitation-related changes sometimes found following its application are poorly understood.

**Errorless learning and cognitive control.** Many of the studies cited above highlight the potential usefulness of errorless learning in the rehabilitation of memory difficulties following M/S TBI. However, the studies leave considerable room for clarification regarding the role of errorless learning as it pertains to neural changes in performance monitoring and cognitive control. Indeed, Dou et al. (2006) state, "the exact mechanism of how errorless learning improves memory function is still being determined" (p. 223). Because individuals with M/S TBI have deficits in recognizing and adjusting for errors, and errorless procedures are designed to reduce that deficit by minimizing competing implicit response options, a key question arises as to when and in what way are neural processes influenced by errorless learning.

There are few studies to date examining the neural bases of errorless learning following brain injury. Using fMRI during errorful recognition with DAI patients, Ueno et al. (2009) reported that, "significant activations were observed in the posterior cingulate gyrus and precuneus in the control group, [with] precuneus and bilateral inferior parietal lobule [activations] in the DAI group" (p. 294). The authors suggest that this broader recruitment of the parietal lobes during errorful learning tasks may be necessary for DAI patients' attempts to perform at a level similar to controls. Using fMRI, Hammer, Tempelmann, and Munte (2013)

reported activations in the left lateralized fronto-temporal-parietal network of neurologically healthy participants learning face-name associations with errorless and errorful methods. This neuroanatomical network included the anterior and posterior cingulate cortex, a structure critical for the efficient exercise of error processing and cognitive control. In addition, a transcranial direct current stimulation (tDCS) study found that cathodal (inhibitory) stimulation applied to the left prefrontal cortex "hampered encoding and memory retrieval after errorful learning but not errorless learning" (Hammer, Mohammadi, Schmicker, Saliger, & Munte, 2011, p. 4). These authors argue that errorful learning is more demanding of executive processes, given the greater degree of retrieval interference, and are thus more susceptible to disturbance with cathodal tDCS.

The findings of these studies illustrate the differential activation of brain injured and healthy individuals both across tasks and across learning conditions. Furthermore, they shed greater light on the role of neuroanatomical structures contributing to memory performance, and highlight the importance of considering whether or to what degree certain cognitive functions are disrupted in clinical populations. Given the demonstrated and potential variability of intervention success across learning conditions, tasks, and clinical populations, further research is needed to clarify the neuroscience of errorless learning in survivors of M/S TBI.

## Errorless Learning and Event-related Potentials

The neural mechanisms behind errorless learning are poorly understood and very little research is available that combines the temporal sensitivity of electroencephalogram (EEG) methods with errorless techniques (and none that include TBI). An important aspect of clinical and research applications of EEG involves event-related potentials (ERPs), which are patterns of neural activity that are bounded, or locked, within a particular time-frame surrounding the onset

of a stimulus or behavioral response. Electroencephalogram is particularly useful given its high temporal resolution--recording electrophysiological information with millisecond accuracy.

As mentioned previously, cognitive control is often impaired following M/S TBI and includes deficits in performance monitoring—including poor ability to monitor for errors (Larson, Kaufman, et al., 2007). One of the more common ways to assess performance monitoring is using the error-related negativity (ERN). The ERN is a negative deflection in the scalp-recorded ERP that peaks within 100ms following the commission of an error (Falkenstein, Hohnsbein, Hoormann, & Banke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993). The ERN is consistently localized to the ACC, a structure central to the evaluative and regulatory processes involved with performance monitoring and cognitive control (Dehaene, Posner, & Tucker, 1994; van Veen & Carter, 2002a). The ERN is applicable for better understanding the neural changes associated with the implementation of cognitive rehabilitation tasks (such as errorless learning) following head injury. The exact functional significance of the ERN is still under debate, and the following is a brief summary of each of the current theories of ERN generation and modulation (c.f. Olvet & Hajcak, 2008; Taylor, Stern, & Gehring, 2007).

The conflict monitoring theory posits that the ACC is engaged in the "detection of conflict occurring between competing, concurrently active, mutually incompatible representations" (Carter & Van Veen, 2007, p. 367) rather than just error detection (Olvet & Hajcak, 2008). Proponents of this model explain that the ERN is a reflection of increased activity in the ACC as it detects conflict and then signals for greater cognitive control in the DLPFC, which then allocates attentional resources to reduce the conflict (Carter & Van Veen, 2007). With more cognitive resources, and reduced conflict, the brain is better able to maintain and/or adjust performance to meet the demands of the task.

Proposed by Brown and Braver (2005, 2007, 2008), the error likelihood model holds that ACC activity increases (resulting in greater ERN amplitude) when there is a greater probability of making a mistake. Their explanation is based on research demonstrating that even in the absence of conflict, or even error commission, the perceived probability of making an error results in increased ERN amplitude. This is corroborated by the fact that in tasks with a disproportionately greater number of trials that require NO responses, the fewer (although correct) YES responses result in greater ERN amplitude (Heldmann, Markgraf, Rodríguez-Fornells, & Münte, 2008). Furthermore, Brown and Braver state that not only does the ACC monitor the likelihood of error, but also the predicted magnitude of consequences should an error occur. Thus, in order to avoid risk, the ACC improves cognitive control by recruiting needed cognitive resources.

The reinforcement learning theory of the ERN proposes that the ACC receives input from various motor control systems (e.g. orbitofrontal, prefrontal cortex) and acts as a control center to "decide" which motor system will actually be implemented. The basal ganglia monitors ongoing events and evaluates present performance. These evaluations regarding performance are communicated to the ACC via the mesencephalic dopamine system. In this manner, the ACC "learns" which actions are most adaptive/useful and consequently is able to signal for adjustments in performance based on available information. The ERN is a reflection of signals from the mesencephalic dopamine system to the ACC. This model is supported by findings that changes in ERN amplitude correlate with dopamine levels, with dopamine and ERN amplitude having an inverse relationship (Holroyd & Coles, 2002; Holroyd, Larsen, & Cohen, 2004).

Certainly each of these proposed explanations for the meaning of the ERN and the function of the ACC and surrounding areas are valuable, and represent pieces of the emerging

puzzle of error processing. In sum, ERP waveforms are useful indicators of cognitive processing, and the ERN in particular is a reliable and putatively valid index of performance monitoring and error processing.

There are four published articles to date that combine ERN waveforms and errorless learning methods, with none of them examining individuals with head injury or other neurologic dysfunction. Rodriguez-Fornells, Kofidis, and Münte (2004) tested neurologically healthy adults, and randomly intermixed errorful and errorless trials while EEG was recorded. Results of their study indicated that both correct hits and incorrect false alarms in both errorless and errorful conditions elicited an ERN. However, correct rejections and missed trials resulted in "small to absent" ERN waveforms in both conditions" (pp. 169-170). The authors interpreted these unexpected results in the context of the conflict monitoring model of the ERN (Carter & Van Veen, 2007), suggesting that participants were experiencing co-activated response tendencies (e.g. thinking a word was familiar and being inclined to respond in the affirmative, but also simultaneously doubting their performance and thinking the word is perhaps incorrectly recognized). They also state that the degree of conflicting memory retrieval has bearing on the production of the ERN, with reduced or absent ERN waveforms on the correctly rejected and missed trials resulting from a lack of the production of a competing response (i.e., identifying a word as unfamiliar- even if that is not the case).

To clarify these results, Heldmann et al. (2008) investigated errorless and errorful conditions in separate experiment blocks. Their findings replicated Rodriguez-Fornells et al., (2004). Specifically, there were no significant ERN amplitude differences between errorless and errorful conditions with correct rejection and missed trials. However, there was "a significant influence of the subjects' judgment regarding whether or not an item had been learned during the

study phase. Surprisingly, the correctness of the subjects' recognition had no significant influence on ERN amplitude variations" (p. 66). These findings led Heldmann and colleagues to the conclusion that the ERN seems more indicative of the perceived probability of making an error (error likelihood model), rather than actual response conflict or error monitoring processes.

A few years later, Hammer, Heldmann, and Munte (2013) investigated the impact of two degrees/levels of conflict in an errorful vs. errorless learning task of face-name associations. The ERN was similar for the errorless trials and for the trials with more interference (more non-target information), with the intermediate interference errorful condition being relatively attenuated compared with the other two conditions. Also, the benefits of errorless learning seemed to decline across trials, while performance in errorful trials improved, suggesting that increased exposure reduces the relative disadvantage of errorful trials. Given the nature of the task and associated findings, the authors again concluded that results were more consistent with the error likelihood model than error detection or conflict monitoring theories of the ERN.

In the only study to date examining errorless learning using the ERN in a clinical population, Hammer et al. (2009) found errorless learning enhanced memory performance in both obsessive compulsive (OCD) and control groups. Controls showed increasingly greater ERN amplitudes for errorless hits, errorful hits, and errorful false alarms respectively. Surprisingly, individuals with OCD showed the opposite pattern; with errorless hits resulting in the most negative amplitude, followed by errorful and errorless hits. In other words, following errorless trials individuals with OCD exhibited an increase in ERN amplitude compared to controls. However in the errorful condition wherein conflict is traditionally increased (i.e., more

competing information) ERN amplitude declined in participants with OCD; the opposite of ERN amplitudes in control participants.

Hammer et al. (2009) cite the work by Brown and Braver (2007, 2008) to try to explain this finding by stating individuals with OCD have an altered ACC learning rate, and this is supported by research showing individuals with OCD have difficulties making simple decisions. When there is more conflict, and it is more likely that OCD participants will make a mistake, the ERN amplitude is not as pronounced because they have a slow ACC learning rate. The authors conclude that there is an altered conflict monitoring system and perceived error-likelihood effects in OCD and state that this is possibly due to a hyperactive monitoring system. In other words, the less conflict that exists when making a decision (the "easier" the choice) the more the ACC is activated because OCD participants doubt the choices they make.

Because Hammer et al. (2009) is the only errorless learning ERN study including a clinical population and results suggest an altered conflict monitoring system in the individuals with OCD, the currently proposed research becomes particularly relevant. That is, that the neural time course and ERP amplitude of error processing in survivors of TBI undergoing errorless learning needs to be investigated and understood.

## Study Aims and Hypotheses

The potential benefits of errorless learning in a cognitive rehabilitation context are encouraging, yet results in more severe neurological populations are mixed and there is little research as to the efficacy of errorless learning in individuals with M/S TBI. If errorless learning could be better understood and applied, rehabilitation outcomes could potentially become more successful and be achieved more quickly. Given the heterogeneity of deficits experienced by survivors of M/S TBI, including deficits in cognitive control, research is currently lacking

regarding the efficacy of errorless learning in this population. Most studies to date, though valuable, have not included sufficiently thorough comparisons within this clinical category; either lacking a comparison group (whether for an errorful condition or for a neurologically healthy control group), or key cognitive performance variables such as executive functioning, processing speed, memory, and attention indices.

Current understanding of the neural mechanisms behind errorless learning is limited. To date, no research has combined errorless learning and ERP/EEG methods to study M/S TBI patients and investigate the neural mechanisms and time course underlying this aspect of cognitive rehabilitation. This lack of research indicates a significant gap in our current understanding of the neural mechanisms behind errorless learning with M/S TBI patients and could help clarify the processes underlying the improvement observed in some errorless learning practices. Given these holes in the literature, the goal of the present research was to conduct a controlled comparison of errorless and errorful learning in individuals with M/S TBI and to clarify the neural time course of the ERN in the same sample and conditions. These goals are achieved by addressing the following specific aims.

**Aim 1**

The 1st aim was to confirm whether survivors of M/S TBI would have impaired performance relative to the demographically matched control group generally, and relatively improved performance on the errorless condition specifically.

**Hypothesis 1.** Survivors of M/S TBI would demonstrate significantly faster reaction times and improved accuracy following errorless vs. errorful learning. Differences between errorless learning and errorful learning conditions would be less pronounced for controls.

**Hypothesis 2.** Among TBI participants, those with greater memory impairments would experience greater benefit from errorless learning (improved accuracy and reaction time). In other words, poor memory would be predictive of proportionally greater gains in performance using errorless learning.

**Aim 2**

The 2nd aim was to confirm that M/S TBI participants exhibit attenuations in ERN amplitude and increased ERN latency relative to controls, and determine whether and/or to what degree the ERN more closely matches healthy controls following errorless learning rather than errorful learning. Amplitude and latency of the ERN following errorless learning was investigated because it is a marker of performance monitoring, and by extension, cognitive/evaluative control in survivors of M/S TBI.

**Hypothesis 1.** Given research to date that demonstrates individuals with greater impairment in cognitive control have attenuated (less negative) ERN amplitude (Larson, Kaufman, et al., 2007), we predicted that the M/S TBI group would have less negative ERN amplitude across learning conditions when compared to matched controls. We also predicted increased ERN latency in the TBI group relative to controls.

**Hypothesis 2.** Survivors of M/S TBI with less negative ERN amplitude (i.e. greater impairment in cognitive control) would show a proportionally greater benefit from the errorless condition. We did not hypothesize a significant difference in ERN amplitude between conditions in control participants due to the higher probability of a ceiling effect in the errorless condition for that group.

# Method

## Participants

The Brigham Young University (BYU) Institutional Review Board (IRB) approved all study procedures and all participants provided written informed consent. Thirty individuals with M/S TBI (10 female) and 29 demographically-similar, neurologically- and psychologically-healthy control participants (8 female) were initially recruited for the study. Participants were recruited via flyers placed throughout the BYU campus and local community, including medical centers and local brain injury support groups. Online advertising was also utilized via IRB-approved ads on www.facebook.com. All participants were financially compensated $10/hour or provided course credit for participation.

Survivors of M/S TBI were enrolled who experienced a M/S TBI six months or more prior to participation. We chose to only enroll individuals at least six months post injury to provide some control with regard to the degree of spontaneous recovery, and increase the probability of having more stable symptoms (Myburgh et al., 2008; Novack, Alderson, Bush, Meythaler, & Canupp, 2000). Participants with uncorrected visual impairments, language comprehension deficits, or pending litigation were excluded from study participation. Moderate and severe TBI was defined according to the criteria outlined in Table 1 (Bigler, 1990; Bond, 1986; Gerstenbrand & Stepan, 2001; Lezak et al., 2012).

Table 1

*Injury Severity Classification*

| | PTA | LOC | GCS |
|---|---|---|---|
| Moderate | 1-7 days | .5-6 hours | 9-12 |
| Severe | >7 days | >6 hours | <9 |

*Note.* PTA = Post Traumatic Amnesia; LOC = Loss of Consciousness; GCS = Glasgow Coma Scale.

To determine injury severity information, participants either brought medical records with them to the study or signed authorization forms for release of medical information specific to their injury and treatment. Medical records were received from 25/30 participants with TBI. Information regarding injury severity was collected from participants via structured interviews similar to those used by Larson, Perlstein, Demery, and Stigge-Kaufman (2006), that have demonstrated validity and reliability (King et al., 1997; McMillan, Jongen, & Greenwood, 1996). Participants were asked specific questions about their injury, what they remembered, and when it occurred (e.g., what is the last thing you remember before the accident?). Participants were asked to distinguish between what they remembered and what they had been told in order to clarify the presence and/or duration of PTA and LOC. Where possible, information was collected from significant others in order to get a more comprehensive view of the injury. There were no significant differences in duration of PTA or LOC between those with and without medical records ($F < .88$, $p > .36$). Participants were classified as moderate or severe if any of the three criteria in Table 1 were met, and generally, classification was easily established. In the few circumstances when criteria was not met or not consistent in two or more classification categories, the third index was often well above the necessary threshold to establish severity.

One participant did not meet the moderate-to-severe criteria based on time of injury characteristics (i.e., PTA = ~8 hours, LOC ~2-3 minutes) but was included in analyses due to a

report consistent with a moderate injury and complicated/extended TBI recovery. Specifically, this individual reported that due to lack of insurance, medical intervention was minimal and after discharge from the ER proceeded to sleep ~16 hours a day for the first 6 days after the injury, and experienced chronic/ongoing cognitive complaints. Furthermore, this case was not an extreme outlier on any neuropsychological or electrophysiological variables relative to the TBI group (see below for how outlying values were determined and handled). Analyses conducted with and without this participant included confirmed no meaningful change in results, and so this case was included in order to improve statistical power.

For the respective goals of aim 1 and aim 2, the inclusion of participant data for analyses proceeded as follows. Two TBI participants were excluded from all analyses in both aims: one TBI participant due to dyslexia which interfered with the efficient reading/processing of words within the timeframe allowed by the word recognition task, and another due to a computer malfunction when no data were recorded.

In addition, four participants (2 TBI, 2 Control) were excluded from final analyses of the EEG data in Aim 2 due to online EEG data recording errors, and 13 more were excluded (7 TBI, 6 Control) due to too few useable segments and/or excessive artifact/noise. Previous research indicates that in order to have a sufficiently reliable ERN, six or more trials are necessary (Olvet & Hajcak, 2009; Pontifex et al., 2010). Consequently, participant data was included only if a participant had six or more usable error trials on both errorless and errorful conditions. Final useable data for Aim 1 included 28 TBI survivors (9 female) and 28 controls (9 female), while useable data for Aim 2 included 19 TBI survivors (6 female) and 20 controls (8 female). A list

of TBI participant injury characteristics, aim inclusion, and whether or not medical records were received is provided in Table 2.

Table 2

*Description of TBI Participant Injury Characteristics and Aim Inclusion*

| Aim 1 (Bx) | Aim 2 (EEG) | Records | Age | Sex | Injury | Time | LOC | PTA | GCS | Rater |
|---|---|---|---|---|---|---|---|---|---|---|
| X | | X | 38 | F | MVA | 174 | 672 | 672* | 3 | X |
| X | X | X | 26 | M | MVA | 52 | 0.5 | 30.5 | * | X |
| X | X | X | 22 | F | Fall | 23 | 240 | 273.5 | 3 | X |
| X | X | X | 29 | M | MVA | 128 | 0.1 | 96.1 | 14 | X |
| X | X | X | 22 | M | ATV | 85 | 504 | 504* | 7 | X |
| X | X | X | 23 | M | MVA | 38 | 384 | 443 | 4 | X |
| X | | X | 31 | M | Assault | 130 | 192 | 201 | * | X |
| X | X | X | 41 | F | Bicycle | 54 | 0.1 | 8.1 | * | |
| X | | X | 19 | F | Fall | 77 | 0 | 90 | * | X |
| X | | X | 27 | F | Assault | 80 | 504 | 516 | * | X |
| X | | | 49 | M | Bicycle | 79 | 18 | 18** | 15 | X |
| X | | | 52 | M | MVA | 88 | 120 | 368 | 14 | X |
| X | | X | 27 | M | Board | 33 | 480 | 480* | 9 | X |
| X | | X | 31 | M | Moto. | 132 | 4 | 3244 | * | |
| X | X | X | 44 | M | Assault | 22 | 0.1 | 408.1 | 13 | X |
| X | X | X | 23 | F | ATV | 49 | 288 | 4608 | 3 | X |
| X | | X | 24 | M | Bicycle | 15 | * | 168 | * | X |
| X | X | X | 53 | M | Fall | 77 | 12 | 1092 | 3 | |
| X | X | X | 30 | M | Snow | 59 | 1008 | 1008* | * | X |
| X | X | X | 52 | F | MVA | 8 | 96 | 132 | 13 | X |
| X | X | X | 36 | M | ATV | 9 | 72 | 72** | 8 | X |
| X | X | X | 22 | M | Moto. | 14 | 3 | 8 | 12 | X |
| X | X | X | 38 | M | Snow | 186 | 500 | 500* | 4 | X |
| X | X | X | 44 | F | MVA | 55 | 0 | 36 | * | X |
| X | X | | 27 | F | MVA | 81 | 90 | 110 | * | X |
| X | X | | 36 | M | Bicycle | 128 | 35 | 95 | * | X |
| X | X | | 22 | M | Snow | 14 | 0.25 | 60.25 | * | X |
| X | X | X | 22 | M | Board | 72 | 408 | 408** | 6 | |
| | | Mean: | 32.5 | -- | -- | 70.1 | 208.6 | 558.9 | 8.2 | |
| | | SD: | 10.4 | -- | -- | 48.0 | 259 | 991.9 | 4.5 | |

*Note.* LOC = Loss of consciousness (in hours); PTA = Post-traumatic amnesia (hours); GCS = Glasgow Coma Score; Time = Months since injury; MVA = Motor Vehicle Accident; ATV = All-terrain vehicle accident; Moto. = Motorcycle; Snow = Skiing, Snowboarding, or Sledding; Board = Skateboard or Longboard; Bx = Behavioral; EEG = Electrophysiological/Event-related potential; Rater = Significant other rating of executive functioning via the FrSBe; X = Included in Aim and/or present; * = Unknown or not provided; PTA values followed by * indicate unknown PTA that includes LOC only. ** = PTA scores of zero that include LOC.

**Aim 1: Demographic and injury characteristics.** Among those participants included in Aim 1 (28 TBI survivors and 28 controls), three participants were ambidextrous, and the rest were right handed; 1 was Hispanic, 1 Asian, 1 Native American, and the rest Caucasian. All participants were between the ages of 19 and 53 years old. Approximately 2/3 of TBI participants were male (n = 19), a result consistent with findings from other studies that report males are more than twice as likely as females to sustain a TBI (Frost, Farrer, Primosch, & Hedges, 2013; Langlois, Rutland-Brown, & Wald, 2006). There were no statistically significant differences between control and M/S TBI groups on age, education, or IQ scores (premorbid estimate of IQ, see below), as can be seen in Table 3.

Table 3

*Demographic and Injury Variables for Aim 1*

| | TBI | | Control | | Difference | |
|---|---|---|---|---|---|---|
| Variable | Mean (SD) | Range | Mean (SD) | Range | *F* | *p* |
| Age | 32.44 (10.6) | 19-53 | 31.8 (10.6) | 19-54 | 0.06 | 0.81 |
| Edu | 14.36 (2.2) | 11-22 | 14.7 (1.5) | 12-18 | 0.41 | 0.53 |
| FSIQ | 106 (8.5) | 84-120 | 109 (5.1) | 99-117 | 1.83 | 0.18 |
| LOC | 208.6 (264) | 0-1008 | -- | -- | -- | -- |
| PTA | 558.9 (1010.1) | 8-4608 | -- | -- | -- | -- |
| GCS | 8.2 (4.7) | 3-15 | -- | -- | -- | -- |
| Time | 70 (48.9) | 8-186 | -- | -- | -- | -- |

*Note.* LOC = Loss of consciousness (in hours); PTA = Post-traumatic amnesia (hours); GCS = Glasgow coma scale; Time = Months since injury; FSIQ = Full Scale IQ based on North American Adult Reading Test score. Group differences examined using one way ANOVAs.

**Aim 2: Demographic and injury characteristics.** Among those participants included in Aim 2 (19 TBI survivors and 20 controls), 2 participants were ambidextrous, and the rest were right handed; 1 was Asian, 1 Native American, and the rest Caucasian. All participants were between the ages of 21 and 53 years old, with 13 TBI participants being male (with 12 male

controls). There were no statistically significant differences on age, education, or estimated IQ (see Table 4).

Table 4

*Demographic and Injury Variables for Aim 2*

| | TBI | | Control | | Difference | |
|---|---|---|---|---|---|---|
| Variable | Mean (SD) | Range | Mean (SD) | Range | *F* | *p* |
| Age | 32 (10.6) | 22-53 | 32 (10.7) | 21.7 - 54.4 | 0.04 | 0.95 |
| Edu | 14 (1.6) | 11-16 | 15 (1.6) | 12 - 16 | 0.85 | 0.36 |
| FSIQ | 106 (7.2) | 90-118 | 109 (5.3) | 99-117 | 1.54 | 0.22 |
| LOC | 150 (164) | 0-408 | -- | -- | -- | -- |
| PTA | 603 (1348) | 0-4320 | -- | -- | -- | -- |
| GCS | 8 (4.7) | 3-14 | -- | -- | -- | -- |
| Time | 44 (38.5) | 8-128 | -- | -- | -- | -- |

Note: LOC = Loss of consciousness (in hours); PTA = Post-traumatic amnesia (hours); GCS = Glasgow coma scale; Time = Months since injury; Edu = Years of education; FSIQ = Full Scale IQ based on North American Adult Reading Test score. Group differences examined using one way ANOVAs.

## Procedures

Upon arrival to the lab each participant reviewed and signed a consent form and were informed of study procedures. Participants were assigned an identification number to preserve confidentiality in record keeping and which dictated the order of errorless and errorful sessions. Neuropsychological assessment and questionnaire data were administered before or after sessions in a counterbalanced fashion. Within the testing battery, the AVLT was administered first in order to allow sufficient time to complete the long delay recall trial. Verbal Fluency was completed after the completion of the AVLT to avoid contamination of list learning. Prior to task administration (errorless or errorless learning), participants were measured and fitted with a Geodesic hydrocel 128 electrode net. Participants were then administered the first learning trial of either the errorless or errorful condition (order counterbalanced). Following completion of the first learning condition, participants were invited to take a mental break while net impedance was

again monitored and the next condition cued. Detailed descriptions of each task and the words used are provided in the following paragraphs. All testing and procedures were completed during a single appointment of approximately 3 hours.

**Task**

**Words used in learning conditions.** Many of the words used in the current study were compiled and pilot tested by Tailby and Haslam (2003) who made their list so that all words were easily visualized nouns, no two target words began with the same two letters, and all target words had four or more possible words that could complete the 2-letter stems. Words were organized into lists based on word length (i.e. same number of 5- and 6-letter words). A list of new distracter words was also generated, combining 12 distracters borrowed from Tailby and Haslam's original list, with 28 more words compiled by the experimenter. These additional words (a total of 20 per list, 60 per condition) were necessary in order to have a sufficient number of trials for an appropriate signal-to-noise ratio during aim 2. Additional words were generated using online word finder software from www.a2zwordfinder.com and then manually filtered by the experimenter to meet the criteria of other word lists mentioned above (e.g., having 5-6 letters, and 4 or more possible alternative words using the first two letters). The function of the distractor list was to test for complete word recognition rather than recognition of the first two letters only. In total, three lists of 20 words each were generated for both the errorless and errorful conditions: one list as a target list, one as a distractor list, and a third as an unrelated list. All words used in the task are available in Appendix A.

**Errorless and errorful procedure.** A summary diagram of the experiment is located in Figure 1, and is helpful for conceptualizing the flow of the learning conditions. The learning procedure closely followed that of Hammer and colleagues (2009; as briefly reviewed above). In

the errorless condition, participants were told the first two letters of a word and then told the actual word. For example, the experimenter said, "I'm thinking of a word that starts with B-R. The word is 'Bread.'" Participants were then asked to repeat the word aloud without making any guesses as to what other words start with "BR." In the errorful condition, participants were told the first two letters of a word (e.g., "BR") and then asked to guess what the word might be. After two guesses (e.g., BROWN, BROKEN) participants were told what the target word was. If they failed to guess a sufficient number of correct words after 20 seconds, the target word was stated by the examiner and non-target words were introduced (e.g., "you also could have guessed 'broom' or 'brown', but 'bread' is correct"). If participants correctly guessed the target errorful word on the first try (which occurred more often as blocks were completed), non-target words were provided by the experimenter in order to ensure the presence of distracters associated with the target word (e.g., "'broom' or 'brown' are other words you could have guessed, but 'bread' is correct"). In both the errorless and errorful conditions, this process occurred for 20 words, and was repeated 6 times (with order of word presentation being pseudorandom for each block) with recognition trials between each block (explained below).

Following each word learning block, participants were asked to identify 20 "target" words on a computer screen that were randomly intermixed with 20 distracter words (words that are similar to the targets) and 20 unrelated words. Words were presented in all caps, centered in white font (Arial 18pt), on a black 17inch LCD screen approximately 20 inches from the participant's head, for 300ms, with variable intertrial intervals (ITI) of 1800, 2100, and 2500ms to decrease expectancy effects. Target words were identified by a button press with the pointer finger of the right (i.e., dominant) hand, and non-target words were identified by a button-press with the middle finger of the same hand. No feedback regarding accuracy was provided during

recognition blocks. Behavioral data such as reaction times (RTs) and accuracy were collected concurrently with EEG recording (see below), which occurred only during recognition blocks. Stimulus presentation and performance recording was accomplished using E-Prime 2.0 software (Schneider, Eschmann, & Zuccolotto, 2002). Participants completed a total of 720 trials, comprised of two sessions with 6 blocks of 60 trials each.

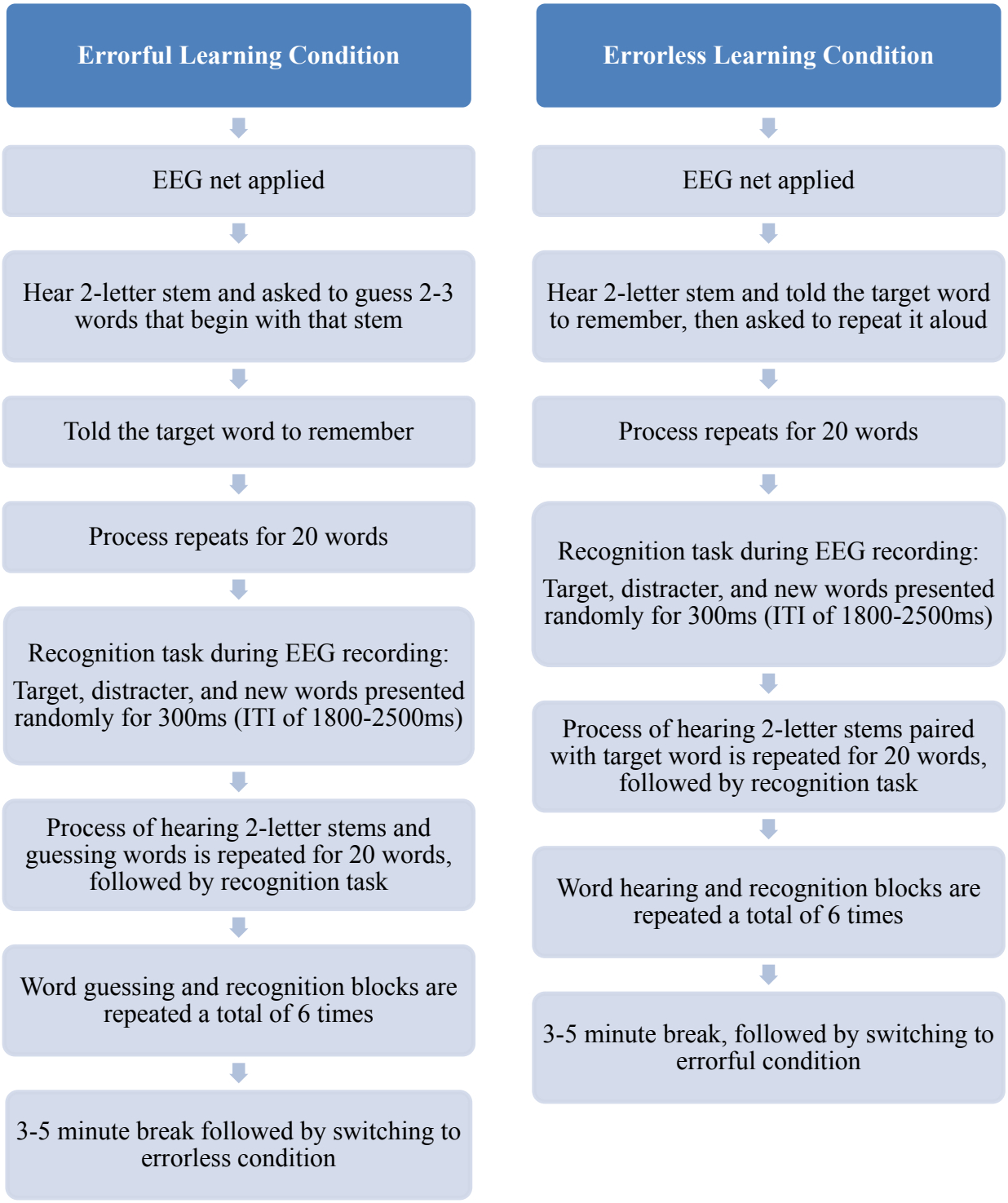


*Figure 1. Task outline*

Both groups participated in errorless and errorful learning conditions, with the order of administration counterbalanced between learning condition as well as word list (e.g. List A or B) within conditions. In this way, any effects from order of administration for condition or word list were controlled. There were no significant differences in accuracy between the word lists used in either condition for either group ($F$s $\leq$ 1.96, $p$s > .17) nor when groups were combined ($F$s $\leq$ .99, $p$s $\geq$.32). With regard to performance over time (i.e., comparing session 1 with session 2 regardless of learning condition), there was no significant difference between sessions for the TBI group ($T_{WJt}$/c[1.0,27.0] = 2.00, $p$ = 0.20) nor the Control group ($T_{WJt}$/c[1.0,27.0] = 2.75, $p$ = 0.15). However, participants with TBI differed significantly in performance from controls in session 2, but not session 1. This is most likely due to the effect of fatigue over time, given that controls showed improvement from session 1 to session 2, and there were no significant differences between groups on the first session. Descriptive statistics for these sessions are visible in Table 5.

Table 5

*Descriptive Statistics for Accuracy Across Learning Sessions*

| | TBI Group | | Control Group | | Differences | |
|---|---|---|---|---|---|---|
| | Mean (SD) | Range | Mean (SD) | Range | *t* | *p* |
| Session 1 | .88(.12) | .54 - .98 | .89(.15) | .37 - .99 | .29 | 0.60 |
| Session 2 | .84(.18) | .35 - .98 | .94(.05) | .82 – .99 | 8.30 | 0.01 |

*Note.* Descriptive statistics using winsorized data. *t* and *p* values reflect arcsine transformed data. Group differences examined using robust ANOVAs.

**Assessment of Mood and Neuropsychological Functioning**

The potential impact of affective sequelae is important to take into consideration when evaluating (and treating) survivors of M/S TBI. Participants completed a short battery of mood/emotional functioning measures and neuropsychological tests to quantify mood symptoms

and to assess/characterize cognitive functioning. Measures were administered via "paper-and-pencil" as well as with an online survey tool (www.qualtrics.com).

**Clinical assessment.** Participants completed the following self-report questionnaires to evaluate general clinical well-being and quality of life.

***SF-36v2.*** The SF-36 is a 36 item self-report questionnaire (Maruish & DeRosa, 2009) that is commonly used to measure quality of life and well-being in eight health areas: physical and social functioning, limitations due to physical and emotional problems, pain, vitality, mental health, and health perceptions. Changes in health are also assessed (Coons, Rao, Keininger, & Hays, 2000). The SF-36 is a reliable measure (internal consistency 0.78), and is validated for the subjective assessment of health related quality of life for survivors of TBI (Findler, Cantor, Haddad, Gordon, & Ashman, 2001).

***Frontal Systems Behavior Scale (FrSBe)***. The FrSBe is a 46-item behavior rating scale originally designed to measure behavioral change associated with frontal lobe injury. The FrSBe gathers information regarding behavioral changes from the patient (self-report) and significant other; however, the FrSBE also includes self- and other ratings of premorbid behavior. The FrSBE includes an overall composite score and three subscales that include questions assessing apathy, disinhibition, and executive function. The FrSBE shows excellent reliability (internal consistency 0.96; split half 0.93) and validity (Grace & Malloy, 2001).

***Hospital Anxiety and Depression Scale (HADS)***. The HADS is a 14-item self-report measure that assesses anxiety and depression in a population that is likely to have significant physical symptoms unrelated to psychological phenomena (Bjelland, Dahl, Haug, & Neckelmann, 2002). Its limited use of items that might be endorsed by non-depressed patients with physical symptoms that are similar to depression makes it valuable for assessing survivors

of TBI and is validated to do so in that population (Whelan-Goodinson, Ponsford, & Schönberger, 2009). The HADS shows good reliability, with a Cronbach's alpha between .81 and .90, and good correlational validity with gold standard measures of depression and anxiety (.67 to .75; Bjelland et al., 2002).

***Positive and Negative Affect Schedule (PANAS).*** The PANAS is a self-report measure consisting of two 10-item mood scales developed to provide a brief measure of positive and negative affect (Watson, Clark, & Tellegen, 1988). Watson et al. (1988) reported Cronbach's alphas between .86 and .90 for the positive affect scale, and .84 to .87 for the negative affect scale. The authors also reported that indices of distress, depression, and anxiety were more highly correlated with the negative affect scale. Several studies have used the PANAS in neurological populations, including TBI (Conrad, Doering, Rief, & Exner, 2010; Man et al., 2004).

**Neuropsychological testing.** Participants also completed the following neuropsychological tests to indicate levels of cognitive performance. All neuropsychological and mood data were converted to z-scores according to publisher norms except for Trails and Verbal Fluency which used metanorms from Mitrushina and colleagues (2005), the RAVLT according to Schmidt (1996) metanorms, the HADS from Crawford, Henry, Crombie, and Taylor (2001), and the PANAS using norms from Crawford and Henry (2004).

***North American Adult Reading Test (NAART).*** This tests is used in neuropsychological evaluations as a measure of premorbid intelligence after brain injury or the onset of dementia (Strauss, Sherman, & Spreen, 2006). The NAART is a good estimate of WAIS-R and WAIS-III overall intelligence composite scores, especially in the average range of intellectual abilities (Johnstone, Callahan, Kapila, & Bouman, 1996); however, the NAART may tend to

overestimate low IQ scores and underestimate high IQ scores (Johnstone et al., 1996). The NAART is "among the most reliable tests in clinical use" with reliability estimates .90 or higher (Strauss et al., 2006, p. 196).

***Digit Span forward and backward.*** In the digit span forward test of the WAIS-III, increasingly longer strings of numbers are recalled (1-9 letters). In the backward version, participants repeat the numbers in reverse order. Span length is defined as the numbers of digits recalled correctly before two strings of the same length were failed. Reliability estimates of the 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 Parts A and B.*** Trails A and B are well-documented measures of visual scanning, processing speed, and task switching (Lezak et al., 2012). The TMT consists of two parts. In Part A, participants connect consecutively numbered circles, while in Part B, participants connect consecutively numbered and lettered circles that alternate between the two sequences. Psychometric studies indicate reliability coefficients above .80 (Strauss et al., 2006), and 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). 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***. These measures are generally presented as a single test. In the COWA, participants are asked to produce as many words as possible in one minute that begin with the letters F, A, and S. Participants are instructed to avoid using proper names and words that are only changed based on different

suffixes (e.g., eat, eating). Similarly, for semantic or category fluency participants are asked to name as many animals as possible in one minute. This measure is used to assess executive functioning and language fluency (Benton, 1994; Gladsjo et al., 1999).

***Rey Auditory Verbal Learning Test (RAVLT).*** The RAVLT is a brief measure for the assessment of immediate memory, new learning, and recognition memory. The measure is a list of 15 nouns that are read aloud to the participant. Following each of five trials, the participant is asked to perform a recall task by repeating the words back to the administrator. The measure has a test retest reliability of r = .60 to .70 and strong construct validity (Rey, 1958).

**Electrophysiological Data Recording, Reduction, and Measurement**

Electroencephalogram data 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). Electrode placements enabled recording vertical and horizontal eye movements reflecting electro-oculographic (EOG) activity. Data from the EEG was referenced to the vertex electrode and digitized continuously at 250Hz with a 24-bit analog-to-digital converter. A right posterior electrode approximately two inches behind the right mastoid served as common ground. Electrode impedance was maintained near 50kΩ.

Electroencephalogram data were filtered using a 30 Hz lowpass filter and a 0.1 Hz highpass filter. 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. Eye blinks were removed from the segmented waveforms using independent components analysis (ICA) in the ERP PCA Toolkit (Dien, 2010) using EEGLAB (Delorme & Makeig, 2004). The ICA components that correlated at 0.90 or higher

with the scalp topography of two blink templates (one internal to the lab, one by the ERP PCA toolkit authors) were removed from the data.

Epochs were response-locked and extracted with a duration beginning 300ms prior to stimulus response, and ending 800ms after response, with -300 to -100ms serving as baseline. As noted above, the ERN is a negative deflection in the ERP that peaks within 100ms following the commission of an error (Falkenstein et al., 1991; Gehring et al., 1993). Therefore, the ERN was identified and averaged across participants using an adaptive mean (adaptive mean refers to identifying the peak negative amplitude then averaging for a period around the peak) of 15ms before and after the most negative amplitude deflection 0-100ms following an incorrect response. The adaptive mean is considered superior to mean peak amplitude given that it reduces the potentially spurious impact of group-wise latency differences as well as noise on the true signal (Clayson, Baldwin, & Larson, 2013).

The amplitude of the ERN was determined from the averaged activity from electrode sites 6, 7, 106, and Cz (see Figure 2), as these sites are consistent with the scalp location of the ERN in previous studies and consistent with the current scalp maps reviewed below (Gehring et al., 1993; Larson, Fair, et al., 2011; Larson, Kaufman, et al., 2007), and demonstrated the strongest amplitudes in the medial frontal region. We used averages across multiple sensors for electrode selection due to research that indicates averaging across multiple electrodes improves reliability of ERP measurement (Baldwin, Larson, & Clayson, 2015; Huffmeijer, Bakermans-Kranenburg, Alink, & van Ijzendoorn, 2014). The ERN difference score was calculated using the difference in amplitude between correct and error trials (error minus correct) to subtract general response-related activity and ensure amplitude ranges were specific to error trials. Latency data for the ERN were identified as the negative peak between 0-100ms post response.

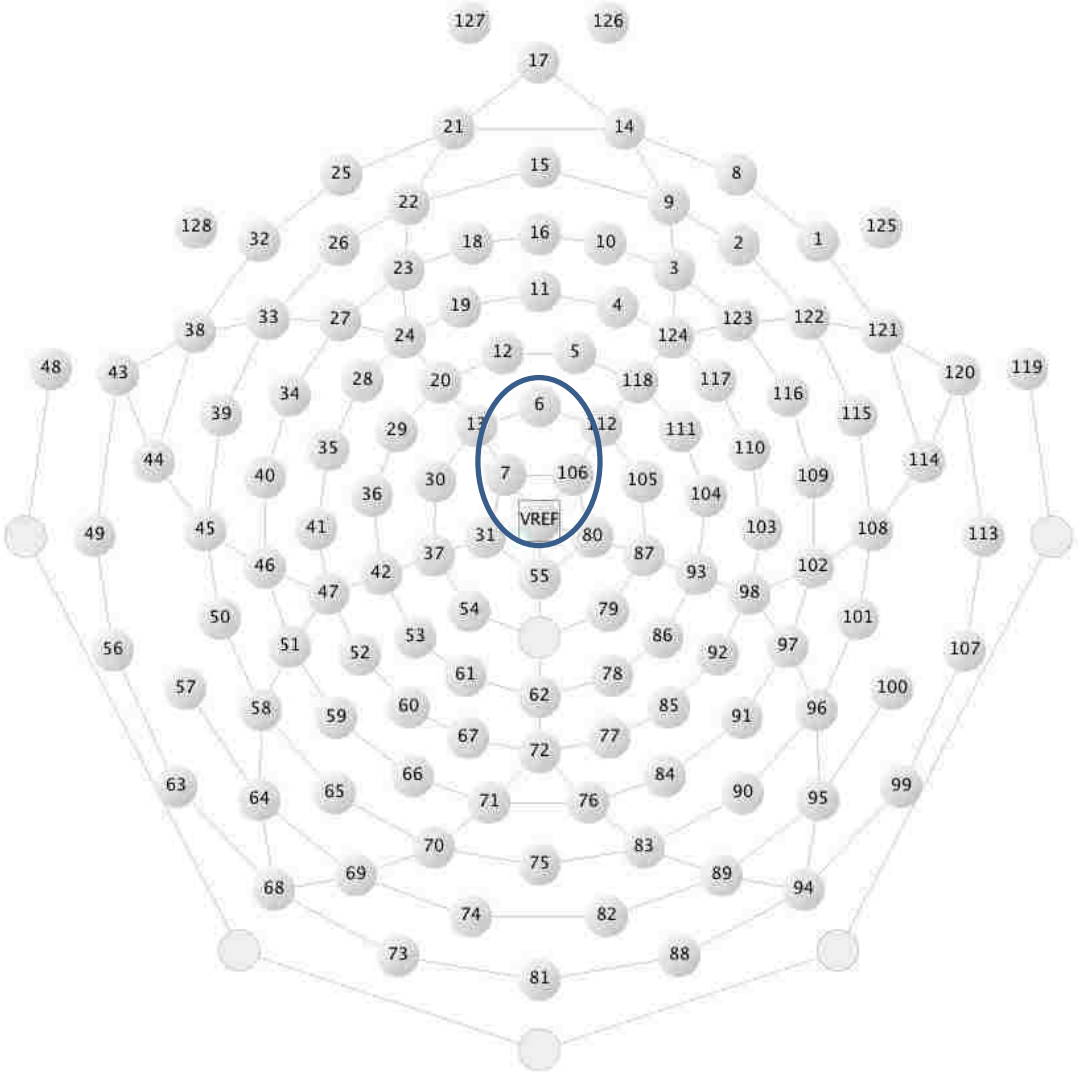


*Figure 2. ERN Component Electrode Locations.*

**Statistical Analyses**

The statistical software packages JMP Pro 9 (SAS Institute, Cary, NC), SPSS 21 (SPSS IBM, New York, NY) and the ERP PCA Toolkit (Dien, 2010) were used for analyses. Verification of the normality of data distribution and equality of variance was completed with visual inspection of box plots and Levene's test (Levene, 1960). Due to some skew and variance differences between groups for some variables, robust ANOVAs were used to test for main effects and interactions, which reduce the impact of assumption violations inherent in traditional ANOVAs. More specifically, robust ANOVA overcome the biasing effects of nonnormality, (co)variance heterogeneity between groups, non-orthogonal groups, and reduce Type I error, but are interpreted similarly to traditional ANOVAs, but (Dien, 2010; Keselman, Wilcox, & Lix, 2003). The seed for the number generation for the robust ANOVAs was set at 1,000, and the number of iterations used for bootstrapping was 50,000 for all robust ANOVA analyses (Clayson & Larson, 2012; Dien, Franklin, & May, 2006; Dien, Michelson, & Franklin, 2010; Larson, Clawson, Clayson, & South, 2012). Significant robust ANOVA interactions were decomposed using Fisher's least significant difference approach, controlling for family-wise Type I error. Accuracy data were arcsine transformed to reduce variance and normalize the proportional data.

Potential outliers were identified by comparing individual data points to the $5^{th}$ and $95^{th}$ percentile of each variable. Scores beyond these minimum and maximum values were evaluated as to whether they represented meaningful or error data, with the conclusion being the former in each case. To address the potential impact of outliers without eliminating cases, values exceeding the $5^{th}$ and $95^{th}$ percentile were winsorized (Wilcox, 2010) to reflect the appropriate minimum or maximum threshold of the distribution (i.e., top and bottom 5%).

Missing data were rare among neuropsych scores or questionnaires (e.g., 2 of 47 participants had missing items from the AVLT). To obtain the most representative dataset, random missing data were imputed using the hot deck imputation method (see Myers, 2011 for review and SPSS syntax). The hot deck method samples from other participants' with similar characteristics and existing (i.e., complete) scores to estimate what the missing value(s) would be, and can include multiple variables as contributing predictors. Some injury characterization data were unavailable from participant report and/or absent from available medical records. Information missing from LOC (n=1), PTA (n=5), and GCS (n=11) variables and FrSBe informant reports (n=4) were not imputed or estimated (i.e., only random single items of scales that were missing were imputed, not full scores).

Robust ANOVAs were used to test for significant group differences due to demographic characteristics. There were no significant between group differences based on age ($T_{WJt}/c[1.0,26.9] = 0.05$, $p = 0.82$), education ($T_{WJt}/c[1.0,16.5] = 0.27$, $p = 0.61$), or estimated IQ ($T_{WJt}/c[1.0,21.0] = 1.09$, $p = 0.31$). There were also no significant main effects of sex on age ($T_{WJt}/c[1.0,26.9] = 1.56$, $p = 0.22$), education ($T_{WJt}/c[1.0,16.5] = 0.01$, p = 0.92, or estimated IQ ($T_{WJt}/c[1.0,21.0] = 0.75$, $p = 0.40$) when looking at TBI and Control groups combined. Furthermore, there were no significant differences between males and females with regard to injury severity (based on available data for GCS, PTA, and LOC; all $ps \geq .12$) or time since injury ($T_{WJt}/c[1.0,17.9] = 0.28$, $p = 0.60$). Given that there were no significant within or between group differences by sex, all further analyses were collapsed across sex.

Means and standard deviations were calculated on neuropsychological, health, and mood assessments, and demographic variables for M/S TBI and control groups. Zero-order correlations were used for correlational analyses. The level of significance for all analyses was

set at the $p = 0.05$ level. Unless otherwise noted, all analyses utilized winsorized data as described previously and were directionalized for consistency in interpretation (with lower values indicating better performance).

**Data Analysis**

**Aim 1.** The purpose of aim 1 was to see if TBI survivors demonstrated faster RTs and better accuracy during errorless learning (hypothesis 1) and if poor memory was predictive of performance during the errorless conditions (hypothesis 2). To test hypothesis 1, a repeated measures 2-Group (TBI, Control) x 2-Condition (errorless, errorful) robust ANOVA was used to examine interactions and main effects. Group was the between-subjects factor, and Condition was the within-subjects factor. Separate robust ANOVAs were calculated for the dependent variables of accuracy (percent correct) overall and for each condition (errorless and errorful), and mean reaction times (RT) overall and for each condition (errorless and errorful). To increase signal-to-noise ratio, hits and correct rejections were paired together as correct trials, and false alarms and misses were paired as error trials. Together, error and correct trials comprised the factor of overall accuracy for each condition.

To test for hypothesis 2, multiple regression was conducted to determine whether or to what degree memory scores and executive functioning predicted accuracy. Variables were converted to z scores based on published normative data, and then averaged to form memory (AVLT total and AVLT long delay scores) and executive functioning (phonemic fluency, Trails B) composites respectively (c.f. Gale & Hopkins, 2004; Larson, Weaver, & Hopkins, 2007). These composites were used as predictors in regression analyses. Indices of multicollinearity were evaluated using the variance inflation factor (VIF), with no models exceeding a VIF of 3.

**Aim 2.** For hypothesis 1 (investigating attenuated ERN amplitude and delayed latency), separate repeated measures 2-Group (TBI, Control) x 2-Condition (errorless, errorful) robust ANOVAs were conducted on the dependent variables of ERN amplitude and ERN latency. As in aim 1, hits and correct rejections were paired together as correct trials, and false alarms and misses were paired as error trials. To test hypothesis 2 (that those with attenuated ERN amplitude would benefit more from errorless learning), multiple regression was conducted to determine whether or to what degree ERN amplitude and latency (independent variables) predicted accuracy (dependent variable). Multicollinearity was tested using VIF, as in Aim 1, with no models exceeding a VIF of 3.

## Results

### Aim 1

**Reaction times.** Reaction times as a function of group and condition are presented in Figure 3. A robust ANOVA indicated a main effect of Group on RT, ($T_{WJt}$/c[1.0,45.4] = 4.89, $p$ = 0.03), with the control group responding faster than the TBI group (see Table 6 for a summary of RT data). There was also a main effect of condition on RT, with both groups responding more quickly in the errorless than errorful condition ($T_{WJt}$/c[1.0,53.8] = 46.18, $p < 0.01$). A Group x Condition x RT interaction was not significant ($T_{WJt}$/c[1.0,53.8] = 0.08, $p$ = 0.77). With regard to correct and incorrect responses, robust ANOVAs indicated a main effect of response type on reaction time ($T_{WJt}$/c[1.0,51.4] = 103.38, $p < 0.01$) with participants as a whole, as well as separately for each group, having faster reaction times on incorrect trials than correct trials (both $p$s < 0.01).

Table 6

*Reaction Time Data for Learning Condition and Trial Type*

| | TBI Group | | Control Group | | Differences | |
|---|---|---|---|---|---|---|
| Condition | Mean (SD) | Range | Mean (SD) | Range | *t* | *p* |
| Errorless | 796(150.6) | 594-1100 | 726(87.9) | 579-890 | 4.55 | 0.04 |
| Errorful | 852(149.4) | 625-1184 | 777(104.3) | 566-946 | 4.72 | 0.04 |
| Correct | 819(146.8) | 612-1133 | 741(86.1) | 582-887 | 0.14 | 0.71 |
| Error | 909(150.7) | 640-1159 | 894(155.7) | 505-1124 | 5.88 | 0.02 |
| Overall | 824(146.7) | 615-1141 | 751(91) | 579-908 | 5.02 | 0.03 |

*Note.* Winsorized data. Group differences examined using robust ANOVAs.

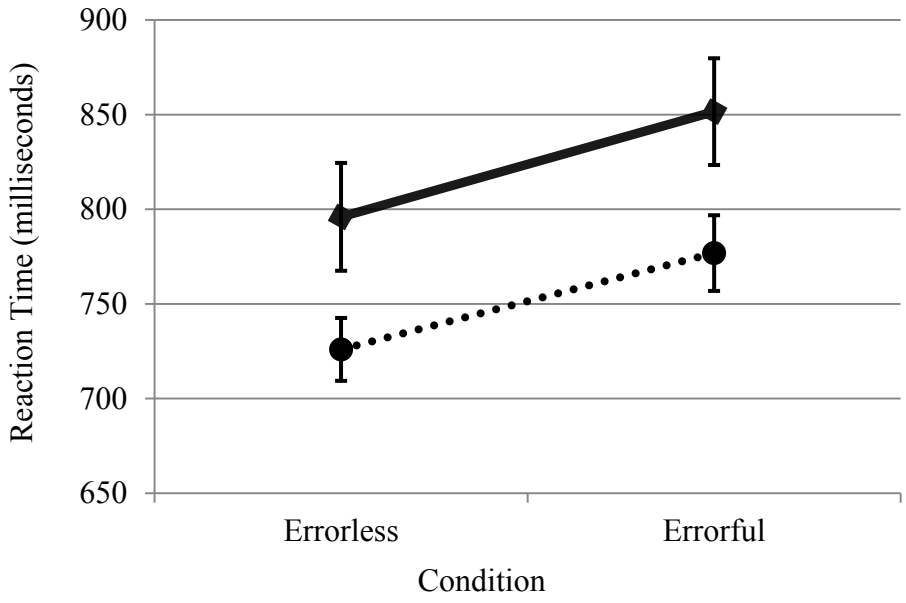


*Figure 3. Reaction times by group and condition*
*Note.* Error bars = +/- 1 Standard Error, Solid line = TBI group, Dash line = Control Group

**Accuracy.** A Group x Condition (errorless, errorful) robust ANOVA almost demonstrated a significant main effect of learning condition on accuracy ($T_{WJt}/c[1.0,52.5] = 4.39$, $p = 0.07$), and a main effect of group was very close to reaching statistical significance ($T_{WJt}/c[1.0,47.8] = 3.87$, $p = 0.06$). Control participants performed more accurately, with mean accuracies of 94% and 89% on errorless and errorful trials respectively. The TBI group had a

mean accuracy of 87% on errorless trials, and 85% on errorful trials (see Table 7 and Figure 4). There was no significant Group x Condition x Accuracy interaction ($T_{WJt}/c[1.0,52.5] = 0.99$, $p = 0.33$).

Table 7

*Percent Accuracy Data by Learning Condition*

| | TBI Group | | Control Group | | Differences | |
|---|---|---|---|---|---|---|
| Condition | Mean (SD) | Range | Mean (SD) | Range | *t* | *p* |
| Errorless | 87(12) | 48-99 | 94(4) | 83-100 | 7.85 | 0.01 |
| Errorful | 85(17) | 41-98 | 89(16) | 37-99 | 0.97 | 0.33 |
| Overall | 86(13) | 51-98 | 91(8) | 65-99 | 3.08 | 0.08 |

*Note.* Winsorized data. Group differences examined using robust ANOVAs on arcsine transformed data

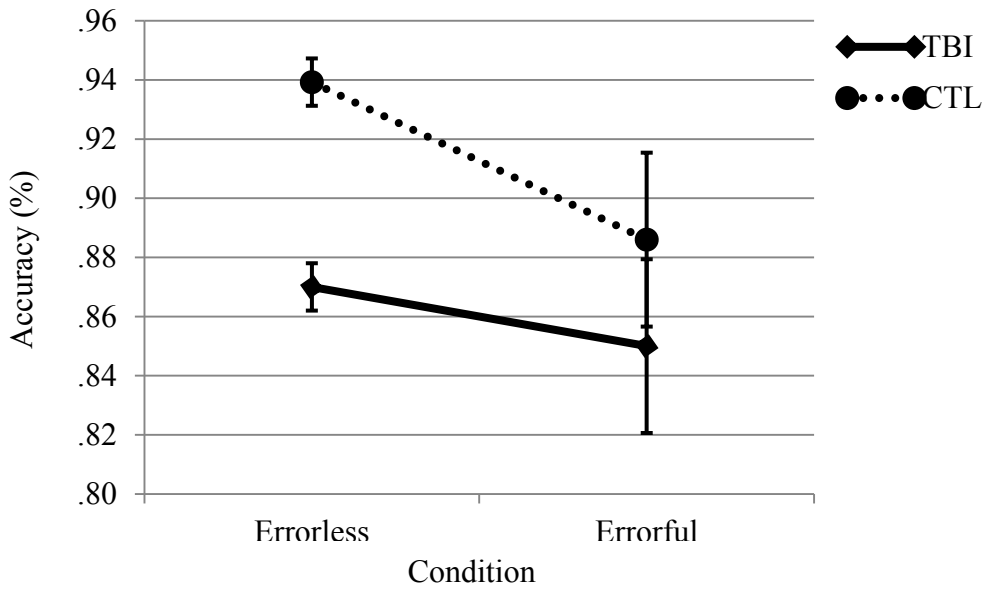


Figure 4. Accuracy data by group and condition
*Note.* Error bars = +/- Standard Error, Solid line = TBI group, Dash line = Control Group

**Self-report measures.** The raw and standardized descriptive statistics of self-report measures from participants included in Aim 1 are outlined in Table 8 and Table 9 respectively. Groups significantly differed on measures of depression and HADS total score, but not with

regard to anxiety, positive affect, or negative affect. Self-report of behavioral and cognitive functioning as measured by the FrSBe indicated no significant differences between controls and survivors pre-injury, but significant differences across all scales (apathy, inhibition, and executive functioning) post-injury. Survivors of TBI and control participants also significantly differed in their ratings of SF-36 mental and cognitive symptoms.

Of the 28 TBI participants included in Aim 1, 25 had family members (typically a spouse or parent) who responded to requests for FrSBe informant-report data. Only those who knew the TBI survivor before and after their injury completed FrSBe questionnaires. Paired-sample *t*-tests did not demonstrate any statistical differences between TBI participants and significant other reports of pre- and post-injury functioning (all $ps \geq .14$) and thus are not included.

Table 8

*Raw Descriptive Statistics for Self-Report Measures for Aim 1*

| | | | TBI Group | | Control Group | | Differences | |
|---|---|---|---|---|---|---|---|---|
| Measure | Domain | | Mean (SD) | Range | Mean (SD) | Range | *F* | *p* |
| FrSBe | Apathy | Pre | 24 (5.8) | 14-39 | 26 (7) | 16-39 | 1.02 | 0.32 |
| | | Post | 32 (7) | 20-47 | 27 (6.9) | 16-39 | 8.74 | 0.00 |
| | Disinhibition | Pre | 25 (4.4) | 17-34 | 24 (5.2) | 15-34 | 0.95 | 0.34 |
| | | Post | 31 (6.3) | 18-42 | 24 (5.1) | 15-34 | 19.43 | 0.00 |
| | Executive | Pre | 31 (7.2) | 18-45 | 33 (7.2) | 20-44 | 0.53 | 0.47 |
| | | Post | 39 (8.4) | 24-54 | 33 (7) | 20-44 | 8.64 | 0.00 |
| | Total Score | Pre | 81 (14.7) | 56-108 | 83 (17.5) | 55-108 | 0.16 | 0.69 |
| | | Post | 102 (18.7) | 65-135 | 83 (17) | 55-108 | 14.76 | 0.00 |
| HADS | Depression | | 5 (4) | 0-13 | 3 (2.6) | 0-10 | 6.47 | 0.01 |
| | Anxiety | | 7 (3.6) | 2-15 | 6 (3.2) | 0-12 | 1.34 | 0.25 |
| | Total Score | | 12 (6.7) | 2-25 | 9 (4.3) | 1-17 | 5.04 | 0.03 |
| PANAS | Negative | | 19 (6.6) | 11-34 | 18 (5.6) | 10-32 | 0.33 | 0.57 |
| | Positive | | 32 (8.7) | 15-44 | 34 (6.4) | 18-45 | 1.03 | 0.31 |
| SF-36 | Mental | | 45 (12.8) | 19-63 | 51 (4.6) | 40-58 | 6.27 | 0.02 |
| | Physical | | 54 (8.7) | 36-69 | 56 (4.3) | 44-61 | 0.99 | 0.32 |

*Note.* Winsorized data. HADS = Hospital Anxiety and Depression Scale; FrSBe = Frontal Systems Behaviors Scale; PANAS = Positive and Negative Affect Schedule. Group differences examined using one way ANOVAs.

Table 9

*Z-Score Descriptive Statistics for Self-Report Measures for Aim 1*

| | | | TBI Group | | Control Group | | Differences | |
|---|---|---|---|---|---|---|---|---|
| Measure | Domain | | Mean (SD) | Range | Mean (SD) | Range | *F* | *p* |
| FrSBe | Apathy | Pre | -0.3 (1.1) | -3.1-2.2 | 0.1 (1.3) | -1.9-2.2 | 1.28 | 0.26 |
| | | Post | 1.2 (1.4) | -1.1-4.1 | 0.1 (1.3) | -1.9-2.2 | 8.11 | 0.01 |
| | Disinhibition | Pre | -0.4 (0.7) | -1.8-1.3 | -0.6 (0.9) | -2.3-1.3 | 0.59 | 0.44 |
| | | Post | 0.6 (1.2) | -1.7-2.9 | -0.6 (0.9) | -2.3-1.3 | 16.98 | 0.00 |
| | Executive | Pre | 0 (1.1) | -2-2 | 0.3 (1.1) | -1.7-2 | 0.63 | 0.43 |
| | | Post | 1.2 (1.3) | -0.8-3.6 | 0.3 (1.1) | -1.7-2 | 7.76 | 0.01 |
| | Total Score | Pre | -0.2 (0.9) | -2.2-1.4 | -0.1 (1.2) | -2.7-1.6 | 0.35 | 0.56 |
| | | Post | 1.2 (1.3) | -1.4-4 | 0 (1.2) | -2.7-1.6 | 12.77 | 0.00 |
| HADS | Depression | | 0 (1.1) | -2.3-1.3 | 0.1 (0.9) | -1.9-1.3 | 4.61 | 0.04 |
| | Anxiety | | 0 (0.8) | -2.3-1 | -0.2 (0.9) | -1.6-2.1 | 1.33 | 0.25 |
| | Total Score | | 0 (1) | -1.9-1.6 | 0 (0.8) | -1.4-1.9 | 3.67 | 0.06 |
| PANAS | Negative | | -0.5 (0.9) | -2.1-0.9 | -0.4 (0.8) | -1.9-1.2 | 0.16 | 0.69 |
| | Positive | | 0 (1.1) | -2.1-1.6 | 0.3 (0.9) | -1.6-1.9 | 0.95 | 0.34 |
| SF-36 | Mental | | -0.5 (1.3) | -3.1-1.3 | 0.1 (0.5) | -1-0.8 | 6.15 | 0.02 |
| | Physical | | 0.4 (0.9) | -1.4-1.9 | 0.6 (0.4) | -0.6-1.1 | 1.02 | 0.32 |

*Note.* Z-scores calculated based on winsorized data. HADS = Hospital Anxiety and Depression Scale; FrSBe = Frontal Systems Behaviors Scale; PANAS = Positive and Negative Affect Schedule. Group differences examined using one way ANOVAs.

**Neuropsychological tests.** Groups significantly differed on measures of working memory, verbal fluency, verbal memory, processing speed, and executive functioning. These results are consistent with common reductions in cognitive functioning following moderate-to-severe TBI. The raw and standardized descriptive statistics of these measures are listed in Table 10 and Table 11 respectively (see also Figure 5).

Table 10

*Raw Neuropsychological Descriptive Statistics for Aim 1*

| | TBI Group | | Control Group | | Difference | |
|---|---|---|---|---|---|---|
| Measure | Mean (SD) | Range | Mean (SD) | Range | *F* | *p* |
| Digit Span Sum | 17 (5.0) | 5-26 | 19 (3.6) | 14-26 | 4.17 | 0.05 |
| FAS Total | 37 (12.4) | 15-63 | 43 (10.6) | 27-65 | 4.26 | 0.04 |
| Animal Fluency | 19 (6.7) | 6-31 | 23 (5.2) | 13-31 | 4.96 | 0.03 |
| AVLT Total | 48 (13.4) | 17-69 | 51 (8.9) | 31-62 | 1.02 | 0.32 |
| AVLT 30m Delay | 8 (4.8) | 0-15 | 11 (3.2) | 5-15 | 6.37 | 0.02 |
| Trails A | 28 (17.6) | 15-85 | 20 (5.4) | 14-32 | 5.37 | 0.02 |
| Trails B | 73 (50.0) | 25-244 | 48 (16.6) | 29-102 | 6.05 | 0.02 |
| NAART Errors | 27 (10.9) | 11-56 | 24 (6.5) | 15-37 | 1.86 | 0.18 |

*Note.* Winsorized data. AVLT = Auditory Verbal Learning Test; NAART = North American Adult Reading Test. Group differences examined using one way ANOVAs.

Table 11

*Z-score Neuropsychological Descriptive Statistics for Aim 1*

| | TBI Group | | Control Group | | Difference | |
|---|---|---|---|---|---|---|
| Measure | Mean (SD) | Range | Mean (SD) | Range | *F* | *p* |
| Digit Span Sum | 0 (1.1) | -2.7-2.3 | 0.5 (0.9) | -0.7-2.3 | 3.89 | 0.05 |
| FAS Total | -0.6 (1.1) | -2.5-1.8 | -0.1 (1) | -1.6-1.9 | 3.97 | 0.05 |
| Animal Fluency | -0.9 (1.4) | -4-1.5 | -0.2 (1.2) | -2.9-1.5 | 4.85 | 0.03 |
| AVLT Total | -0.7 (1.6) | -5.4-1.8 | -0.4 (1.2) | -3.4-1.3 | 0.80 | 0.38 |
| AVLT 30m Delay | -1.1 (1.8) | -4.5-1.5 | -0.1 (1.2) | -2.9-1.7 | 5.76 | 0.02 |
| Trails A | -0.3 (2.2) | -7.5-1.3 | 0.6 (0.7) | -0.9-1.5 | 4.46 | 0.04 |
| Trails B | -0.7 (2.2) | -7.4-1.8 | 0.3 (0.8) | -2.2-2.1 | 4.77 | 0.03 |
| NAART FSIQ | 0.4 (0.6) | -1.1-1.3 | 0.6 (0.3) | -0.1-1.1 | 1.83 | 0.18 |

*Note.* Z-scores calculated based on winsorized data. AVLT = Auditory Verbal Learning Test; NAART FSIQ= estimated full scale IQ based on North American Adult Reading Test performance. Group differences examined using one way ANOVAs.

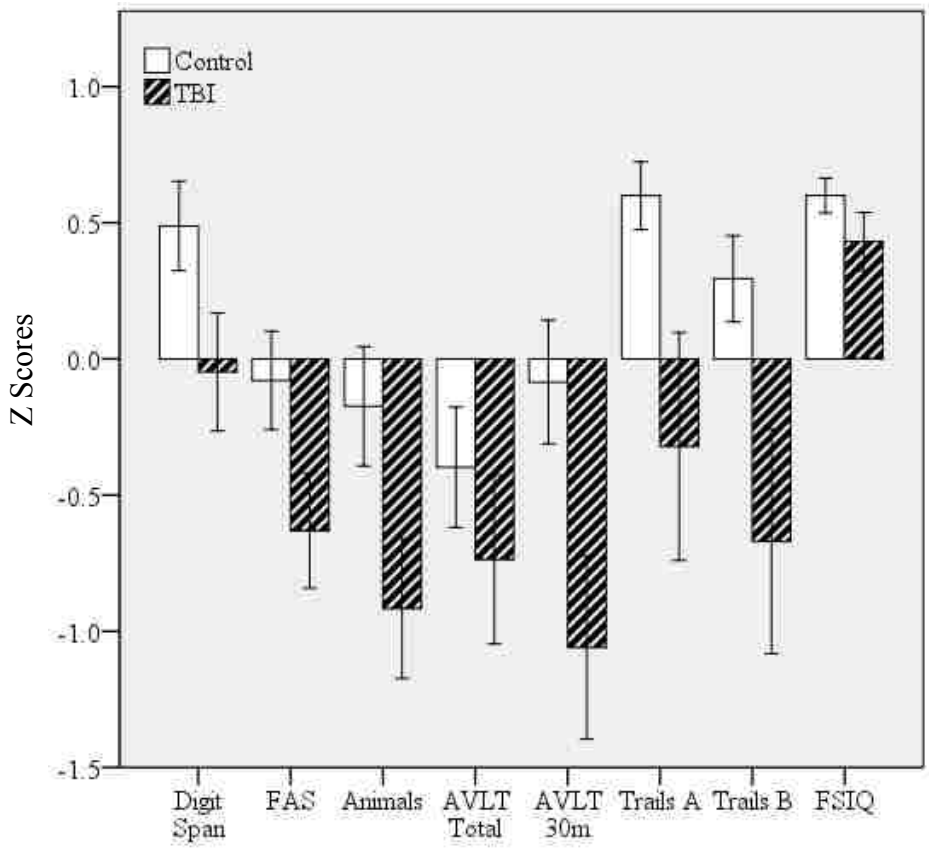


*Figure 5. Neuropsychological Test Performance for Aim 1*

*Note.* Winsorized data transformed to z-scores based on published norms. Error bars: +/- 1 standard error. AVLT = Auditory Verbal Learning Test; FSIQ= estimated full scale IQ based on North American Adult Reading Test performance

In order to gain a better understanding of the relationships among outcome variables of interest and other data such as cognitive and mood functioning, multiple correlation matrices are presented. Although these repeated correlations increase the likelihood of Type 1 error, due to the absence of research in this population using controlled comparisons with errorless learning, the correlations were considered valuable contributions. As can be seen in Table 12, a Pearson correlation matrix indicated that multiple neuropsychological subtests were significantly correlated with accuracy in the errorless condition among TBI participants. However, only memory indices were positively correlated with accuracy in the errorful condition. Correlations among variables in the control group, seen in Table 13, demonstrate that memory indices and Trails B performance were significantly correlated with errorless accuracy and reaction time. Phonemic fluency and Trails B performance were significantly correlated with accuracy on errorful trials, and AVLT total was correlated with reaction time during the errorful condition.

Table 12

*Correlations Between Neuropsychological Tests and Performance (TBI Group)*

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Accuracy EL | 1 | | | | | | | | | | | |
| 2. Accuracy EF | 0.64** | 1 | | | | | | | | | | |
| 3. Reaction Time EL | 0.49** | .28 | 1 | | | | | | | | | |
| 4. Reaction Time EF | 0.66** | 0.43* | 0.92** | 1 | | | | | | | | |
| 5. Digit Span | 0.51** | 0.30 | 0.36 | 0.41* | 1 | | | | | | | |
| 6. FAS Total | 0.38* | 0.21 | 0.19 | 0.38* | 0.55** | 1 | | | | | | |
| 7. Animal Fluency | 0.55** | 0.27 | 0.52** | 0.67** | 0.55** | 0.76** | 1 | | | | | |
| 8. AVLT Total | 0.70** | 0.45* | 0.49** | 0.61** | 0.68** | 0.54** | 0.72** | 1 | | | | |
| 9. AVLT 30Min | 0.66** | 0.54** | 0.53** | 0.64** | 0.48** | 0.4* | 0.68** | 0.86** | 1 | | | |
| 10. Trails A | 0.41* | 0.23 | 0.05 | 0.24 | 0.49** | 0.22 | 0.38* | 0.43* | .33 | 1 | | |
| 11. Trails B | 0.57** | 0.29 | 0.24 | 0.42* | 0.55** | 0.59** | 0.64** | 0.67** | 0.57** | 0.54** | 1 | |
| 12. NAART | 0.61** | 0.31 | 0.38* | 0.56** | 0.69** | 0.49** | 0.65** | 0.64** | 0.52** | 0.48** | 0.56** | 1 |

*Note.* * = $p < .05$, ** = $p < .01$. Variables winsorized and directionalized for consistency. EL = Errorless, EF = Errorful, AVLT = Auditory Verbal Learning Test, NAART = # of errors on the North American Adult Reading test.

Table 13

*Correlations Between Neuropsychological Tests and Performance (Controls)*

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Accuracy EL | 1 | | | | | | | | | | | |
| 2. Accuracy EF | 0.25 | 1 | | | | | | | | | | |
| 3. Reaction Time EL | 0.40* | 0.11 | 1 | | | | | | | | | |
| 4. Reaction Time EF | 0.12 | 0.18 | 0.84** | 1 | | | | | | | | |
| 5. Digit Span | 0.22 | 0.14 | 0.08 | -0.07 | 1 | | | | | | | |
| 6. FAS Total | 0.28 | 0.44* | 0.25 | 0.30 | 0.15 | 1 | | | | | | |
| 7. Animal Fluency | -0.01 | 0.24 | 0.26 | 0.32 | -0.17 | 0.45* | 1 | | | | | |
| 8. AVLT Total | 0.65** | 0.28 | 0.58** | 0.53** | 0.22 | 0.49** | 0.31 | 1 | | | | |
| 9. AVLT 30Min | 0.67** | 0.30 | 0.42* | 0.27 | 0.13 | 0.46* | 0.33 | 0.74** | 1 | | | |
| 10. Trails A | 0.34 | 0.33 | 0.31 | 0.18 | -0.02 | 0.53** | 0.22 | 0.4* | 0.31 | 1 | | |
| 11. Trails B | 0.56** | 0.61** | 0.45* | 0.31 | 0.33 | 0.51** | 0.28 | 0.68** | 0.65** | 0.44* | 1 | |
| 12. NAART | 0.11 | -0.01 | 0.19 | 0.20 | 0.48** | 0.23 | 0.12 | 0.30 | 0.36 | -0.02 | 0.17 | 1 |

*Note.* * = $p < .05$, ** = $p < .01$. Variables winsorized and directionalized for consistency. EL = Errorless, EF = Errorful, AVLT = Auditory Verbal Learning Test, NAART = # of errors on the North American Adult Reading test.

To further test the potential influence of executive functioning and other factors such as mood and health ratings on performance, correlation matrices were generated for both groups and conditions. TBI survivor ratings of physical health were inversely related to accuracy in the errorful condition, but other correlations with performance were not significant (see Table 14). There were no significant correlations among these variables for the control group (Table 15).

Table 14

*Correlations Between Mood/Health Ratings and Performance (TBI Group)*

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Accuracy EL | 1 | | | | | | | | | | | | |
| 2. Accuracy EF | 0.64** | 1 | | | | | | | | | | | |
| 3. Reaction Time EL | 0.49** | 0.28 | 1 | | | | | | | | | | |
| 4. Reaction Time EF | 0.66** | 0.43* | 0.92** | 1 | | | | | | | | | |
| 5. HADS Anxiety | 0.06 | 0.21 | 0.07 | 0.05 | 1 | | | | | | | | |
| 6. HADS Depression | 0.01 | 0.00 | 0.22 | 0.23 | 0.57** | 1 | | | | | | | |
| 7. PANAS Negative | 0.28 | 0.26 | 0.14 | 0.15 | 0.86** | 0.52** | 1 | | | | | | |
| 8. PANAS Positive | -0.05 | 0.03 | -0.13 | -0.11 | -0.62 | -0.78** | -0.62** | 1 | | | | | |
| 9. SF36 Physical | -0.31 | -0.64** | -0.27 | -0.42 | -0.08 | -0.07 | -0.03 | 0.05 | 1 | | | | |
| 10. SF36 Mental | -0.01 | 0.03 | 0.03 | 0.03 | -0.69 | -0.79 | -0.71** | 0.81** | -0.15 | 1 | | | |
| 11. FrSBe Apathy | 0.07 | 0.16 | 0.05 | 0.15 | 0.5** | 0.77** | 0.56** | -0.61** | -0.18 | -0.82** | 1 | | |
| 12. FrSBe Disinhibition | -0.01 | 0.05 | 0.00 | 0.11 | 0.47* | 0.48** | 0.52** | -0.50** | -0.16 | -0.48** | 0.47** | 1 | |
| 13. FrSBe Executive | 0.29 | 0.30 | 0.17 | 0.29 | 0.48** | 0.62** | 0.56** | -0.55** | -0.36 | -0.63** | 0.8** | 0.52** | 1 |

*Note.* * = $p < .05$, ** = $p < .01$. Variables winsorized and directionalized for consistency. EL = Errorless, EF = Errorful, HADS = Hospital Anxiety and Depression Scale, PANAS = Positive and Negative Affect Schedule, SF-36 = Health Survey, FrSBe = Frontal Systems Behaviors Scale, FrSBe variables are post-injury ratings.

Table 15

*Correlations Between Mood/Health Ratings and Performance (Controls)*

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Accuracy EL | 1 | | | | | | | | | | | | |
| 2. Accuracy EF | 0.25 | 1 | | | | | | | | | | | |
| 3. Reaction Time EL | 0.4* | 0.11 | 1 | | | | | | | | | | |
| 4. Reaction Time EF | 0.12 | 0.18 | 0.84** | 1 | | | | | | | | | |
| 5. HADS Anxiety | -0.14 | 0.23 | -0.03 | -0.04 | 1 | | | | | | | | |
| 6. HADS Depression | -0.13 | -0.15 | 0.03 | 0.04 | 0.05 | 1 | | | | | | | |
| 7. PANAS Negative | -0.08 | 0.28 | -0.07 | -0.03 | 0.68** | 0.09 | 1 | | | | | | |
| 8. PANAS Positive | -0.19 | -0.04 | -0.23 | -0.15 | 0.18 | -0.40* | 0.15 | 1 | | | | | |
| 9. SF36 Physical | -0.12 | 0.17 | 0.19 | 0.22 | -0.21 | -0.25 | -0.24 | 0.07 | 1 | | | | |
| 10. SF36 Mental | 0.07 | -0.15 | -0.12 | -0.10 | -0.59** | -0.36 | -0.77** | 0.23 | -0.02 | 1 | | | |
| 11. FrSBe Apathy | -0.23 | 0.06 | 0.06 | 0.16 | 0.37 | 0.39* | 0.37* | -0.39* | 0.12 | -0.66** | 1 | | |
| 12. FrSBe Disinhibit | -0.01 | 0.17 | 0.18 | 0.21 | 0.68** | 0.11 | 0.52** | -0.07 | 0.11 | -0.61** | 0.6** | 1 | |
| 13. FrSBe Executive | 0.06 | 0.41* | 0.13 | 0.24 | 0.52** | 0.17 | 0.34 | -0.22 | 0.13 | -0.43 | 0.63** | 0.74** | 1 |

*Note.* * = $p < .05$, ** = $p < .01$. Variables winsorized and directionalized for consistency. EL = Errorless, EF = Errorful, HADS = Hospital Anxiety and Depression Scale, PANAS = Positive and Negative Affect Schedule, SF-36 = Health Survey, FrSBe = Frontal Systems Behaviors Scale, FrSBe variables are post-injury ratings.

**Regression analyses.** To test the hypothesis that poorer cognitive performance would be associated with greater errorless learning benefit, multiple regression analyses were conducted. Results from the regression models are summarized in Table 16. The "Memory" composite consisting of the average z scores of AVLT Trials 1-5 total and 30minute delayed recall, the "Executive" composite (average of Trails B and phonemic fluency z scores), and Group (TBI and Controls) were used as dependent variables. The overall model was predictive of accuracy on errorless trials ($F$[3,52] = 22.73, $p < .01$), accounting for 57% of the variance in accuracy in this condition. Memory functioning was the only significant independent predictor of errorless accuracy ($p < .01$). In the errorful condition, the same model was also significantly predictive of accuracy ($F$[3,52] = 5.48, $p < .01$), and accounted for 24% of the variance. The memory composite was not significance as an individual predictor of accuracy in the errorful condition ($p = .07$).

In order to test whether or to what degree injury severity was a significant predictor, a subanalysis using only TBI participants was conducted using moderate vs. severe injury as a group predictor rather than TBI vs. control. Other variables remained the same as in previous regression analyses. These results were significant for the errorless ($F$[3,24] = 9.59, $p < .01$; 55% of the variance) and errorful ($F$[3,24] = 9.59, $p = .03$; 32% of the variance) conditions. However, injury severity was not a significant independent predictor in either model ($ps \geq .30$) and consequently summary tables are not included.

Table 16

*Multiple Regression Models with Condition Accuracy as Dependent Variables and Group, Memory, and Executive Functioning as Predictor Variables*

| Variables | $R^2$ | Adj. $R^2$ | *p*-value | *B* *(Std. Error)* | Beta | *p*-value | VIF |
|---|---|---|---|---|---|---|---|
| **DV: Accuracy on EL** | 0.57 | 0.54 | 0.00 | | | | |
| Group | | | | .05(.03) | 0.17 | 0.08 | 1.11 |
| Executive | | | | -.02(.02) | -0.19 | 0.14 | 1.79 |
| Memory | | | | -.06(.01) | -0.56 | 0.00 | 1.71 |
| **DV: Accuracy on EF** | 0.24 | 0.20 | 0.00 | | | | |
| Group | | | | -.01(.05) | -0.02 | 0.89 | 1.11 |
| Executive | | | | -.04(.03) | -0.26 | 0.12 | 1.79 |
| Memory | | | | -.04(.02) | -0.29 | 0.07 | 1.71 |

Note. Executive and Memory composites based on winsorized, z scored data. Accuracy scores were winsorized and arcsine transformed. DV = Dependent variable, EL = Errorless condition, EF = Errorful condition, Adj. = Adjusted; Group = TBI and Control; Executive = Trails B and phonemic fluency averaged z-scores; Memory = Auditory Verbal Learning Test total and long delay averaged z-scores.

HADS Anxiety and Depression combined scores, PANAS Negative scores, and Group were also used as predictors in a separate regression, as seen in Table 17. The model was significant for accuracy in the errorless condition ($F$[3,52] = 3.91, $p$ = .01; accounting for 18% of the variance) but not the errorful condition ($F$[3,52] = 1.98, $p$ = .13). Group was a significant independent predictor of accuracy in the errorless condition ($p$ < .01), with PANAS Negativity as the only significant predictor in the errorful condition ($p$ = .04).

Table 17

*Multiple Regression Models with Condition Accuracy as Dependent Variables and Negative Affect Endorsement as Predictor Variables*

| Variables | $R^2$ | Adj. $R^2$ | *p*-value | *B (Std. Error)* | Beta | *p*-value | VIF |
|---|---|---|---|---|---|---|---|
| **DV: Accuracy on EL** | 0.18 | 0.14 | 0.01 | | | | |
| Group | | | | .12 (.04) | 0.41 | 0.00 | 1.13 |
| HADS Total | | | | -.01 (.01) | -0.26 | 0.16 | 2.11 |
| PANAS Negativity | | | | .01 (.00) | 0.33 | 0.06 | 1.94 |
| **DV: Accuracy on EF** | 0.10 | 0.05 | 0.13 | | | | |
| Group | | | | .06 (.06) | 0.15 | 0.28 | 1.13 |
| HADS Total | | | | -.01 (.01) | -0.17 | 0.37 | 2.11 |
| PANAS Negativity | | | | .01 (.01) | 0.38 | 0.04 | 1.94 |

*Note.* Mood variables are winsorized and directionalized. Accuracy scores were winsorized and arcsine transformed. DV = Dependent variable, EL = Errorless condition, EF = Errorful condition, Adj. = Adjusted, HADS = Hospital Anxiety and Depression Scale, PANAS = Positive and Negative Affect Schedule.

## Aim 2

**Self-report measures.** A summary of group differences on self-report measures are presented in Table 18. Groups significantly differed on a measure of depression, but not on measures of positive and negative affect. Self-report of behavioral and cognitive functioning as measured by the FrSBe indicated no significant differences between controls and survivors pre-injury, but significant differences across all scales (apathy, inhibition, and executive functioning) post-injury. Groups did not differ with regard to positive and negative affect, or physical complaints. However, there were significant differences between groups with cognitive complaints. Correlation matrices indicated that measures of affect did not significantly correlate with ERN amplitude, ERN latency, or accuracy in either learning condition (and are not included).

Table 18

*Descriptive Statistics for Self-Report Measures for Aim 2*

| | | | TBI Group | | Control Group | | Differences | |
|---|---|---|---|---|---|---|---|---|
| Measure | Domain | | Mean (SD) | Range | Mean (SD) | Range | *F* | *p* |
| FrSBe | Apathy | Pre | 23 (5.6) | 14 - 37 | 25 (6.3) | 16 - 39 | 0.07 | 0.80 |
| | | Post | 34 (7.1) | 25 - 47 | 25 (6.4) | 16 - 39 | 12.42 | 0.00* |
| | Disinhibition | Pre | 24 (3.7) | 18 - 29 | 23 (5.4) | 15 - 31 | 1.74 | 0.20 |
| | | Post | 32 (7) | 19 - 44 | 23 (5.3) | 15 - 31 | 19.64 | 0.00* |
| | Executive | Pre | 30 (6.8) | 18 - 42 | 33 (7.8) | 19 - 45 | 0.04 | 0.84 |
| | | Post | 41 (8.6) | 23 - 53 | 32 (7.5) | 19 - 45 | 10.45 | 0.00* |
| | Total Score | Pre | 80 (14.5) | 54 - 108 | 79 (17.6) | 54 - 107 | 0.35 | 0.85 |
| | | Post | 103 (16.8) | 68 - 131 | 80 (17.1) | 54 - 107 | 18.73 | 0.00* |
| HADS | Depression | | 5 (4) | 0 - 13 | 2 (1.7) | 0 - 5 | 12.34 | 0.00* |
| | Anxiety | | 8 (4.1) | 2 - 16 | 5 (3.4) | 1 - 13 | 3.33 | 0.08 |
| | Total Score | | 13 (7.3) | 2 - 25 | 7 (4.0) | 1 - 16 | 9.37 | 0.00* |
| PANAS | Negative | | 19 (7.4) | 11 - 35 | 17 (5.4) | 10 - 31 | .94 | 0.34 |
| | Positive | | 30 (8.9) | 12 - 44 | 34 (7.6) | 14 - 46 | 1.49 | 0.23 |
| SF-36 | Mental | | 44 (14.5) | 18 - 64 | 52 (4.1) | 44 - 59 | 6.73 | 0.01* |
| | Physical | | 54 (10.1) | 36 - 69 | 55 (4.9) | 42 - 61 | 0.31 | 0.58 |

*Note.* Winsorized data. HADS = Hospital Anxiety and Depression Scale; FrSBe = Frontal Systems Behaviors Scale; PANAS = Positive and Negative Affect Schedule; SF-36 = Health Survey.

* $p < .05$ (a significant difference between groups on a one way ANOVA).

**Neuropsychological tests.** Groups did not significantly differ on measures of cognitive functioning (see Table 19). Given the significant differences among the same measures noted in aim 1 (see Table 10) the current results are likely due to reduced sample size.

Table 19

*Neuropsychological Descriptive Statistics for Aim 2*

| | TBI Group | | Control Group | | Difference | |
|---|---|---|---|---|---|---|
| Measure | Mean (SD) | Range | Mean (SD) | Range | *F* | *p* |
| Digit Span Sum | 17 (4.4) | 8 - 24 | 19 (3.3) | 14 - 26 | 2.11 | .15 |
| FAS Total | 39 (12.9) | 19 - 65 | 43 (10.9) | 27 - 64 | 1.27 | .27 |
| Animals | 20 (6.3) | 8 - 31 | 23 (4.4) | 15 - 31 | 2.99 | .09 |
| AVLT Total | 49 (13.0) | 27 - 71 | 50 (8.9) | 30 - 61 | .01 | .91 |
| AVLT 30m Delay | 8 (4.8) | 1 - 15 | 10 (2.9) | 4 - 15 | 2.62 | .11 |
| Trails A | 27 (16.1) | 14 - 71 | 19 (6.0) | 13 - 34 | 3.63 | .07 |
| Trails B | 74 (55.4) | 28 - 270 | 50 (19.8) | 27 - 110 | 3.23 | .08 |
| NAART Errors | 28 (9.1) | 13 - 49 | 25 (6.9) | 15 - 39 | 1.42 | .24 |

Note. Winsorized data. AVLT = Auditory Verbal Learning Test; NAART = North American Adult Reading Test; Animals = Category Fluency. Group differences examined using one way ANOVAs.

**Error-related negativity.** In order to test for between group differences in signal-to-noise ratio, the number of trials retained for averaging of the ERP component ERN were examined. Traumatic brain injury survivors and control participants differed on the number of correct trials retained for averaging, but not error trials (see Table 20). Given that the ERN relies upon error trials rather than correct trials and the number of correct trials is so large, trial number differences between groups are unlikely to influence the reliability of this waveform.

Table 20

*Number of Trials by Condition as a Function of Group*

| | TBI | | | Control | | | Difference | |
|---|---|---|---|---|---|---|---|---|
| Condition | Mean | SD | Range | Mean | SD | Range | *F* | *p* |
| EL Correct | 228.4 | 76.7 | 72-324 | 276.4 | 47.6 | 149-339 | 5.59 | 0.02 |
| EL Incorrect | 27.7 | 20.9 | 6-73 | 18.4 | 9.1 | 6-38 | 3.33 | 0.08 |
| EF Correct | 210.7 | 70.8 | 121-331 | 257.6 | 77.6 | 88-348 | 3.88 | 0.06 |
| EF Incorrect | 41.9 | 54.4 | 6-217 | 30.5 | 33.5 | 7-158 | .64 | 0.43 |

*Note.* Number of trials included in ERP component analyses for the ERN component. EL = Errorless, EF = Errorful. Group differences examined using one way ANOVAs.

Error trial descriptive statistics of the ERN are available in Table 21. Robust ANOVAs indicated a main effect of accuracy in both the errorless ($T_{WJt}$/c[1.0,28.4] = 21.20, $p < 0.01$) and errorful ($T_{WJt}$/c[1.0,26.6] = 17.41, $p < 0.01$) conditions, with error trials having significantly more negative amplitude than correct trials. This suggests the presence of a reliable ERN across conditions. However, there was no main effect of group on ERN amplitude for the errorless ($T_{WJt}$/c[1.0,30.8] = 0.88, $p = 0.36$) or errorful ($T_{WJt}$/c[1.0,37.0] = 1.56, $p = 0.22$) conditions. There were no significant Group x correct- vs. error-trial Amplitude interactions for either condition ($ps \geq .22$), neither were there significant main effects of Condition, Group, or Group x Condition interactions with regard to error-trial Amplitude ($ps \geq .32$). Robust ANOVAs did not reveal any significant main effects of learning condition ($T_{WJt}$/c[1.0,37.0] = 0.89, $p = 0.35$) or group ($T_{WJt}$/c[1.0,34.2] = 0.66, $p = 0.42$) on error trial ERN latency. Non-significant results also occurred for correct trial latency on learning condition and group ($ps \geq 0.33$). Separate correlation matrices for each group did not demonstrate any remarkable associations between injury characteristics (PTA, LOC, GCS, time since injury) and accuracy, ERN latency, or ERN amplitude. When groups were combined, correlation matrices showed a significant inverse

relationship between ERN amplitude on errorful trials and errorful accuracy. There was no significant relationship between ERN amplitude and accuracy on errorless trials.

**Regression analyses.** Using linear regression, ERN latency was not predictive of accuracy for either errorless ($F$[2,36] = 2.76, $p$ = .08) or errorful ($F$[2,36] = .39, $p$ = .68) conditions and accounted for $\leq$ 9% of the variance in accuracy for each condition. Group was a significant independent predictor of accuracy in the errorless condition ($p$ = .05), but not the errorful condition ($p$ = .45). Errorful accuracy was predicted by ERN amplitude on errorful trials ($p$ = .02). Results from the regression models are summarized in Table 22 and Table 23¸ and ERN grand average waveforms are available in Figure 6 and Figure 7 respectively, with topographical representations in Figure 8. These results generally do not support the original hypotheses proposed for aim 2.

Table 21

*Error Trial Descriptive Statistics of ERN Amplitude and Latency*

| | TBI | | | | | | Control | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Errorless | | | Errorful | | | Errorless | | | Errorful | | |
| | Mean | SD | Range | Mean | SD | Range | Mean | SD | Range | Mean | SD | Range |
| ERN Amplitude | -1.94 | 2.85 | -11.1 - .85 | -1.88 | 1.94 | -3.1 - 1.9 | -1.4 | 1.11 | -3.1 - .92 | -1.23 | 1.21 | -3.1- 1.9 |
| ERN Latency | 56.7 | 26.8 | 1 - 99.9 | 55.9 | 24.5 | 2 - 93.9 | 57.4 | 24.2 | 15.6 - 99.6 | 66.1 | 19.2 | 36.2 - 97.8 |

*Note.* Winsorized data. ERN = Error related negativity.

Table 22

*Regression Models with Condition Accuracy as Dependent Variable and ERN Latency as Predictor*

| Variables | $R^2$ | Adj. $R^2$ | *p*-value | *B* *(Std. Error)* | Beta | *p*-value | VIF |
|---|---|---|---|---|---|---|---|
| **DV: Accuracy on EL** | 0.13 | 0.09 | 0.08 | | | | |
| Group | | | | -0.07(0.04) | -0.31 | 0.05 | 1.00 |
| ERN Latency EL | | | | 0.00(0.00) | 0.19 | 0.22 | 1.00 |
| **DV: Accuracy on EF** | 0.02 | -0.03 | 0.68 | | | | |
| Group | | | | -0.05(0.07) | -0.13 | 0.45 | 1.00 |
| ERN Latency EL | | | | 0.00(0.00) | 0.08 | 0.65 | 1.00 |

Note. Latency variables were winsorized and mean-centered. Accuracy scores were winsorized and arcsine transformed. EL = Errorless trials, EF = Errorful trials, ERN = Error related negativity. Adj. = Adjusted, DV = Dependent Variable.

Table 23

*Regression Models with Condition Accuracy as Dependent Variable and ERN Amplitude as Predictor*

| Variables | $R^2$ | Adj. $R^2$ | *p*-value | *B* *(Std. Error)* | Beta | *p*-value | VIF |
|---|---|---|---|---|---|---|---|
| **DV: Accuracy on EL** | 0.16 | 0.11 | 0.04 | | | | |
| Group | | | | -0.08(0.03) | -0.34 | 0.03 | 1.02 |
| ERN Amplitude EL | | | | -0.01(0.01) | -0.25 | 0.11 | 1.02 |
| **DV: Accuracy on EF** | 0.15 | 0.11 | 0.05 | | | | |
| Group | | | | -0.08(0.06) | -0.20 | 0.21 | 1.04 |
| ERN Amplitude EF | | | | -0.05(0.02) | -0.38 | 0.02 | 1.04 |

Note. Amplitude variables were based on the adaptive mean and were winsorized and mean-centered. Accuracy scores were winsorized and arcsine transformed. EL = Errorless trials, EF = Errorful trials, ERN = Error related negativity. Adj. = Adjusted, DV = Dependent Variable.

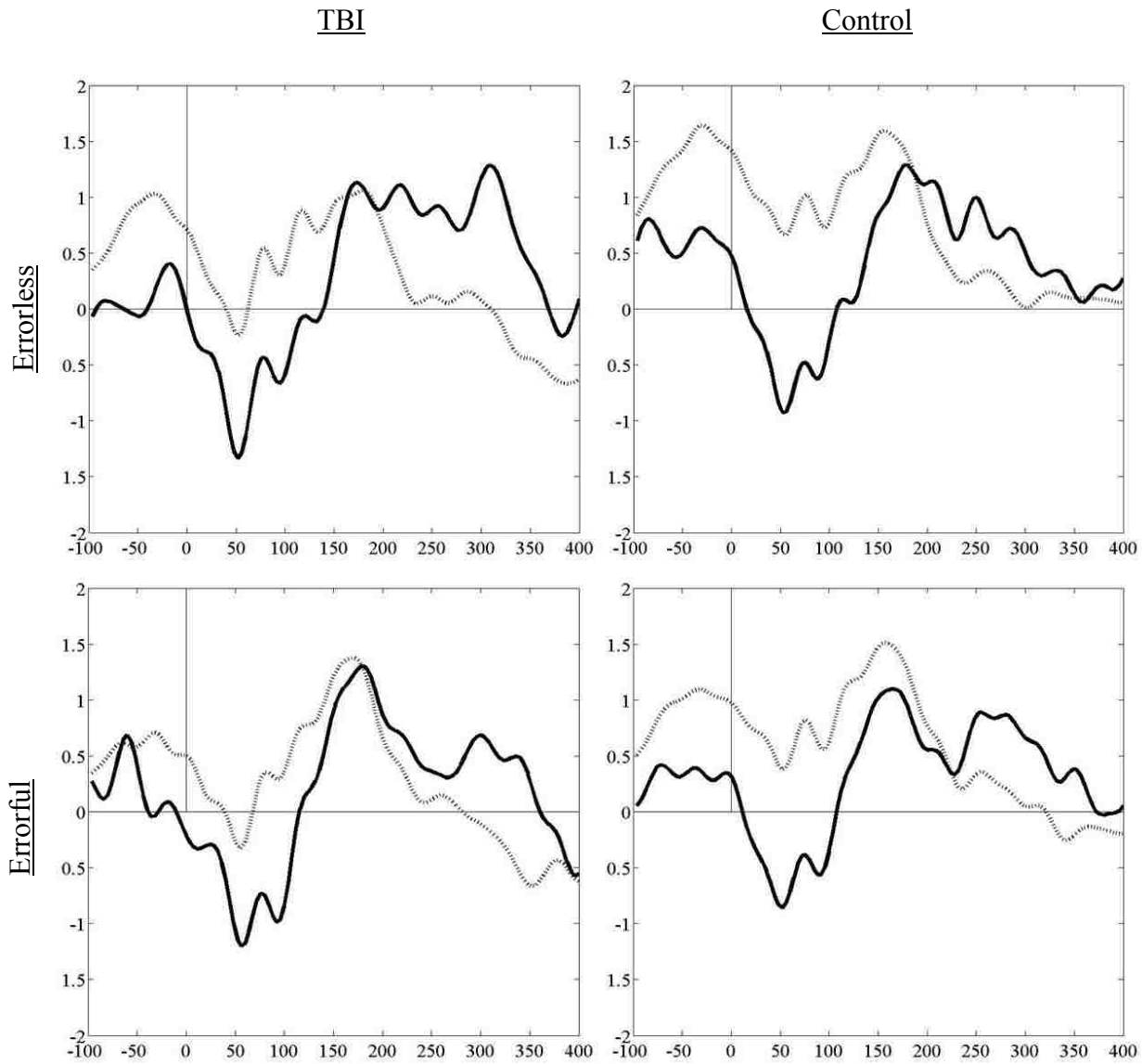


Figure 6. Grand average waveforms for the ERN component by group and condition. Original segmented epochs are response-locked at -300-800ms. The waveforms shown are epoch windows from -100-400ms and correspond to correct (dash line) and error (solid line) trials. Y axis = Amplitude, X axis = Milliseconds.

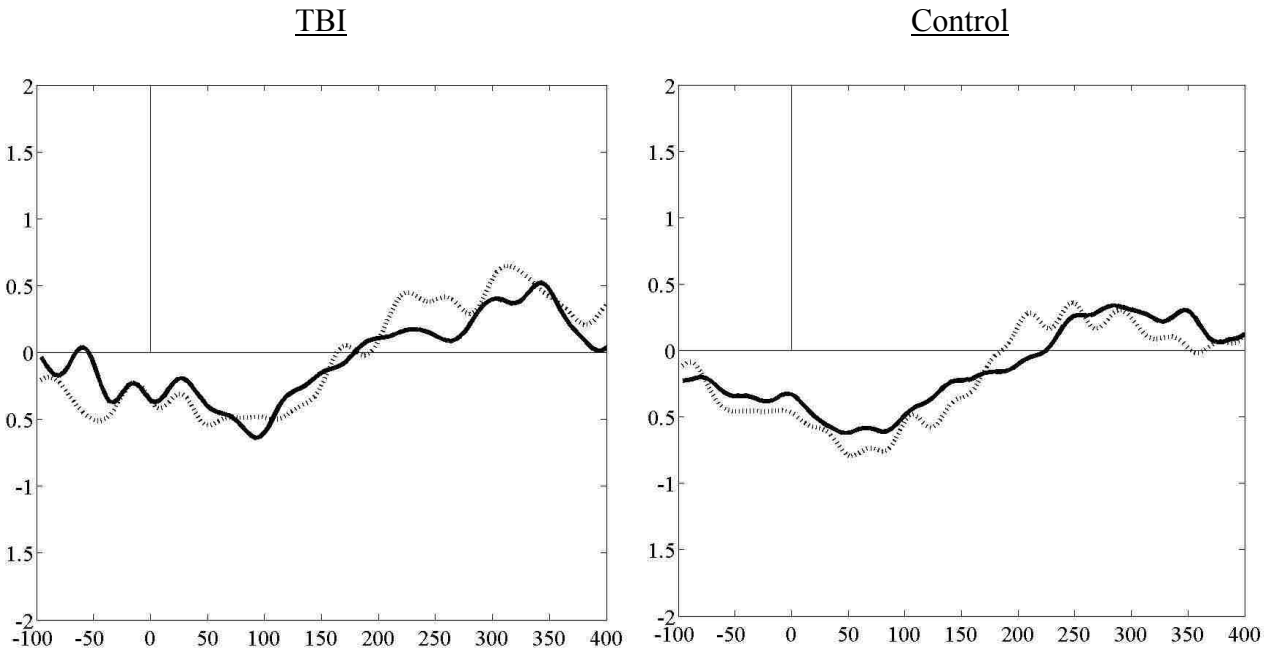


Figure 7. Grand average difference waveforms for the ERN component.
Original segmented epochs are response-locked at -300-800ms. The waveforms shown are epoch windows from -100-400ms and reflect the difference between correct and error trials for errorless (dash line) and errorful (solid line) conditions. Y axis = Amplitude, X axis = Milliseconds.

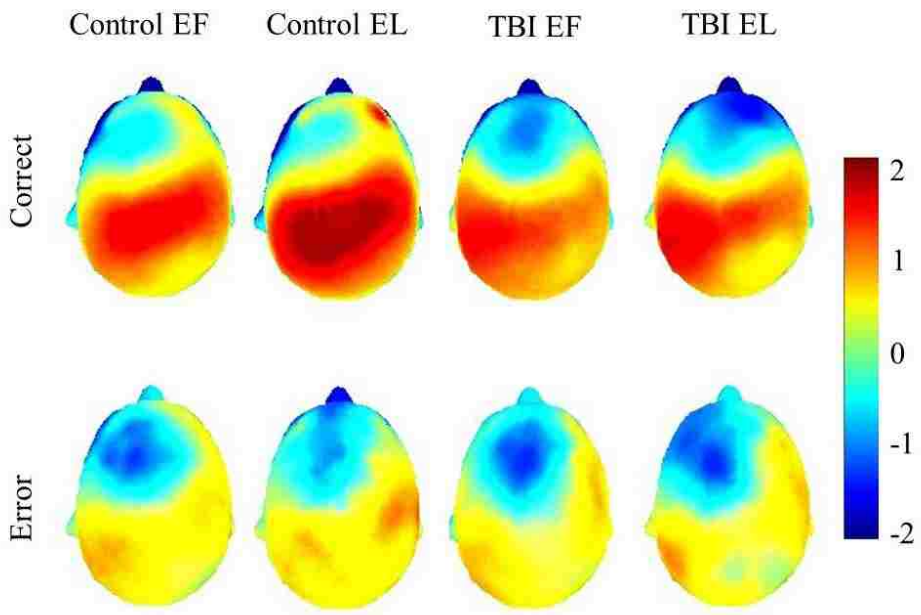


Figure 8. Topographical representation of the ERN component.
Mean voltages in microvolts (μV) between 0-100ms post response for correct and error trials by group and condition. EL = Errorless, EF = Errorful.

## Discussion

Cognitive deficits following M/S TBI are common and varied, including sustained attention, divided attention, memory, working memory, and executive functioning (Lezak et al., 2012; Strangman et al., 2005). Treatment of cognitive dysfunction resulting from M/S TBI can be challenging; however, intensive rehabilitation programs often result in improvements in functioning (Chua et al., 2007). Rohling et al. (2009) state that those with M/S TBI who are treated with cognitive rehabilitation in the first year after injury show significantly greater improvement than those who receive treatment a year or more after their TBI. Considering the substantial time (and monetary) cost of rehabilitation, knowing which therapy is most effective is extremely valuable for maximizing recovery following M/S TBI.

Mount et al. (2007) suggest that in clinical/ rehabilitation settings, the nature of the task to be learned should always be considered, and the learning approach tailored to each patient and context. It is generally accepted that errorless learning is an empirically supported and commonly applied form of cognitive rehabilitation for survivors of TBI (Kessels & de Haan, 2003; c.f., Cicerone et al., 2000; Cicerone et al., 2005; Rohling et al., 2009), although gains with errorless learning are moderated by the nature of the task, with semantic tasks typically more successful than behavioral tasks. The present study was designed to better understand the efficacy of errorless learning, as well as investigate the neural mechanisms underlying errorless and errorful learning in a controlled M/S TBI sample.

### Aim 1

The purpose of aim 1 was to confirm the presence of an errorless learning benefit for survivors of M/S TBI as measured by faster RTs and better accuracy during the errorless learning condition relative to the errorful condition. Results confirmed that both the M/S TBI

and control group responded faster and performed more accurately during errorless vs. errorful trials, although there were statistically significant differences in reaction time between groups (with controls being faster). There was a significant main effect of learning condition (errorless vs. errorful) on RT, an outcome consistent with some studies (Heldmann et al., 2008; Rodriguez-Fornells et al., 2004) but not others (Hammer, Heldmann, et al., 2013). A main effect of condition on accuracy and a main effect of group (M/S TBI, Control) on accuracy were not significant. Survivors of M/S TBI performed worse than controls in terms of accuracy and reaction times, and did not demonstrate statistically significant differences in accuracy between the two learning conditions. There were no significant Group x Condition x RT or Group x Condition x Accuracy interactions, suggesting no differential impact/influence among these variables.

Aim 1 also hypothesized that those with greater memory impairments would experience greater benefit (improved accuracy and reaction time) from errorless vs. errorful learning (Tailby & Haslam, 2003), and that differences in performance among control participants between learning conditions would be unremarkable. Correlations indicated that for TBI survivors, AVLT total and AVLT delayed recall performance (but not other cognitive measures) were significantly correlated with accuracy in the errorful condition. In contrast, all cognitive variables were significantly correlated with accuracy in the errorless condition. Among control participants, phonemic fluency and Trails B (both more dependent upon frontal/executive processes) were the only significant correlations with errorful accuracy, while Trails B and AVLT scores (total and delayed) were the only significant neuropsychological predictors of errorless accuracy. Multiple regression clarified that group (TBI vs. Control), executive functioning (Trails B, phonemic fluency), and memory performance (AVLT total, AVLT delay)

were significantly predictive of errorless learning accuracy, with memory functioning being a significant independent predictor. Although the same overall model was still significant for predicting errorful accuracy (albeit to a lesser degree), memory was no longer a significant independent predictor. Injury severity classification (moderate vs. severe) were used in additional regression models but were not significant independent predictors of accuracy—likely due to the reduction in sample size when trying to examine the moderate and TBI groups separately.

Regression analyses suggest that memory functioning, more so than group status (TBI vs. Control), was the primary contributor to the degree of successful memory performance on errorless trials (but not errorful). That memory functioning would predict memory performance is intuitive; but the problem with this outcome is that the function of errorless learning is to help those who have memory impairments. In contrast, errorful learning accuracy was predicted less by memory specifically and more by group status, memory, and executive functioning in combination. Thus, a possible predictive variable in choosing TBI survivors who are good candidates for EL training is the degree of their memory deficits. Those with better memory performance may be able to better engage in the tasks—pushing toward a more selective recruitment of less severely injured individuals.

Whereas gathering some measurement of cognition or degree of memory impairment is fairly routine in the cognitive rehabilitation literature (even if only a mental status exam), a more thorough exam such as that used in the current study is less common. The use of cognitive variables as predictors in errorless learning studies is rare (Laffan, Metzler-Baddeley, Walker, & Jones, 2010; Warmington, Hitch, & Gathercole, 2013). The current study results contradict those of Warmington et al. (2013) who did not find any of the subtests from a cognitive battery

to be uniquely predictive of errorless learning performance, although vocabulary and processing speed were independent predictors of errorful learning. The inconsistent results between studies may be explained by the fact that Warmington et al. (2013) studied children, using a nonword-object pairings, and utilized different measures of cognition.

For the current study, errorful condition performance being predicted by a wider variety of factors lends support to the idea that errorless learning relies less upon executive functioning processes than errorful learning, facilitating its utility among those with general cognitive compromise following acquired brain injury. Thus, it appears based on this efficacy data that errorless learning has the benefit of reducing executive functioning demands but still requires a significant degree of memory ability to facilitate performance. This conclusion runs counter to the hypothesis that poor memory would be predictive of proportionally greater gains in performance using errorless vs. errorful learning.

However, the finding that errorless learning accuracy depends in part upon existing memory resources has been pointed out in previous studies. For example, Tailby and Haslam (2003) evaluated patients with mild, moderate, and severe memory deficits and found that under standard errorless learning conditions, the moderate group performed significantly better than the severe group (with the mild vs. moderate group differences trending towards significance). They noted that "accuracy in the [errorless] conditions increased as severity of memory impairment decreased" (Tailby & Haslam, 2003, p. 1238). Laffan et al. (2010) used a variation of errorless learning involving self-generation of target information and found that "patients with less severe general cognitive impairment benefit more from active generation than more severely impaired patients" (2010, p. 197).

Additional evidence supports the current study's finding that memory functioning is associated with errorless learning efficacy. Page, Wilson, Shiel, Carter, and Norris (2006) compared patients with moderate and severe memory impairments and, although overall results did not show a strong difference between groups, they noted that "the errorless learning advantage seems to be enhanced in the moderately impaired group" although the statistical interaction was not quite significant (2006, p. 95). Kessels and Hensken, (2009) reported that although errorless learning was clearly superior to errorful learning, "effect sizes are smaller for people with more severe dementia compared to patients with mild-to-moderate dementia," (Kessels & Hensken, 2009, p. 311). These studies highlight that the severity of memory impairment is an additional key factor contributing to (or interfering with) the efficacy of errorless learning methods.

As just described, both M/S TBI and control participants in the current study benefited from errorless vs. errorful learning (although not quite statistically so), with memory functioning being a significant independent predictor of errorless learning efficacy. These results raise the question as to what degree of memory impairment is appropriate and/or most efficacious to apply errorless learning methods (because, again, errorless learning is intended help those who have memory deficits). Although difficult to answer based on current data, Haslam, Hodder, & Yates (2011) aptly summarized the available literature by stating that the errorless learning benefit "may differ as a function of the type of task used, the way memory is tested, and the severity of memory impairment" (p. 433). Clare and Jones (2008) and Middleton and Schwartz (e.g., Clare & Jones, 2008; Middleton & Schwartz, 2012), raised important criticisms against the putative utility of the errorless learning method in certain tasks and clinical populations. Specifically,

stating that the act of evaluation (testing) more so than the act of rehearsal (study) contributes to greater information retention over time.

However, the act of being tested (i.e., formalized free recall of information previously learned) can be conceptualized as an effortful approach to learning, and there is evidence that effort can facilitate retention in clinical populations. Working with Alzheimer's patients, Dunn and Clare (2007) found that not only was errorless learning no more effective than errorful learning in face-name associations, but that high-effort conditions produced better learning performance for novel information following cued recall. Dunn and Clare (2007) conceptualized vanishing cues and forward cueing as being effortful, while paired associates and target selection (i.e. multiple choice) were classified as effortless. The authors concluded that error reduction may be less important than factors such as the degree of cognitive effort involved (albeit within a supportive framework) and the amount of time utilized during training/rehearsal (Dunn & Clare, 2007).

The general findings from the current study, that errorless learning is more effective at improving accuracy and RT than errorful learning, tentatively supports the wide array of research published to date and lends credibility to the errorless learning method. However, the current study's (mixed) results also add credence to other research elaborating on traditional errorless methods, and highlight that cognitive remediation techniques should to be continually updated, enhanced and individually-adapted to increase their utility. Variations like self-generated errorless learning show considerable promise (Cyr & Anderson, 2012; Guild & Anderson, 2012; Laffan et al., 2010; Lubinsky et al., 2009). Combining training methods such as utilizing errorless learning in conjunction with spaced retrieval (having longer and longer delays between rehearsal) may also be useful (Jean et al., 2010; Kixmiller, 2002).

**Negative Affect.** Previous research has demonstrated that affective changes and difficulties are common following brain injury, with the most common emotional symptoms following severe TBI being depression and anxiety, (Silver et al., 2001) with depression and anxiety symptoms frequently co-occurring (Jorge et al., 2004). Negative affect-related changes in cerebral function are associated with deficits in memory, attention, decreased motor functions, and impaired executive functioning (Emerson et al., 2001; Emerson et al., 2005; Mialet et al., 1996; Shenal et al., 2003; Sweeney et al., 2000; Trichard et al., 1995). Larson et al. (2009) found that "negative affect constitutes a significant risk for greater performance-monitoring difficulties" (p.442) in survivors of severe TBI even when accounting for injury severity and length of time post-injury. In anticipation of the presence of negative affect symptoms in some participants, those enrolled in the current study completed several measures of mood functioning in order to control as well as quantify the possible influence of negative affect on dependent variables of interest (RT, accuracy, ERN amplitude, etc).

Although no specific hypotheses were made regarding the role of emotional functioning on errorless learning efficacy, analyses were conducted to determine to what degree negative affect impacted cognitive performance. Controls and M/S TBI survivors significantly differed on measures of depression, HADS total score, SF-36 mental and cognitive symptoms, and all self-report indices of behavioral and cognitive functioning on the FrSBe (apathy, inhibition, and executive functioning). However, groups did not significantly differ with regard to ratings of anxiety, positive affect, or negative affect. Results of regression models indicated that negative affect (more specifically, PANAS negative affect) can interfere with performance on errorless (but perhaps not errorful) learning conditions.

Thus, while not a primary aim of the study, the current results suggest that negative affect can influence performance/functioning and highlights the importance of integrated and comprehensive treatment approaches following TBI that include treatment of affective difficulties as well as cognitive functioning. Of note is that, "improvement in affective functioning is as important to rehabilitation outcomes as improvement in cognitive function" (Prigatano, 2005, p. 118) and "dealing with [emotional reactions] is an integral, not an ancillary part of effective treatment" (Sohlberg & Mateer, 2001, p. 9). Prigatano (2008) outlines through case examples the value of a psychodynamic approach to rehabilitation, and explains that "psychotherapeutic work can help brain dysfunctional patients achieve a greater level of psychosocial adjustment" (p. 991). Various models of therapy may be applicable and useful for the cognitive/affective rehabilitation of M/S TBI survivors, although cognitive-behavioral therapy (CBT) is generally more common, and can be merged with other cognitive neuropsychological rehabilitation methods (W. H. Williams, 2003).

**Aim 2**

Whereas the amount of available research examining the efficacy of errorless learning is substantial, there is very little published data on neural activity associated with errorless learning—either in individuals with TBI or healthy controls. We examined the ERN, an index of error-related performance monitoring, in this regard. Results showed the presence of a typical ERN waveform that was larger on error trials than correct trials for both groups, but did not indicate a significant main effect of group for either learning condition, nor any significant interaction effects (Group x Accuracy, Group x Condition) for error-trial ERN amplitude. Similarly, there were no significant main effects of learning condition or group on error-trial or correct-trial ERN latency, neither was ERN latency a significant predictor of errorless or errorful

accuracy. Furthermore, injury characteristics were not significantly correlated with ERN amplitude, ERN latency, or accuracy. In terms of regression models, group (but not latency) was a significant predictor of accuracy on the errorless condition suggesting that controls performed better overall. ERN amplitude was a significant independent predictor of accuracy on the errorful condition, although errorless ERN amplitude and accuracy did not have a significant relationship. Correlation matrices showed a significant inverse relationship between the errorful ERN amplitude and errorful accuracy.

These generally null findings regarding ERN amplitude between groups and errorless vs. errorful conditions may be partly explained by the fact that participants included in aim 2 did not significantly differ between groups on measures of cognitive functioning. Minimal-to-absent group differences may be partially related to extended time since injury durations, which ranged from 8 months to 10 years. Findings from the current study that confirmed the presence of an ERN but found no significant relationship between ERN amplitude and learning condition (or group) are comparable with previous errorless learning research from neurologically healthy participants (Hammer, Heldmann, et al., 2013; Hammer et al., 2009; Heldmann et al., 2008; but see Rodriguez-Fornells et al., 2004). The paradigms used in Hammer et al. (2009), Heldmann et al. (2008) and Rodriguez-Fornells et al. (2004) all shared some commonalities with the current study. For example, all used errorless list learning with 2-3 letters as the primer, with corresponding errorful learning conditions that required guessing. The only exception is Hammer, Heldmann, et al. (2013) where they taught face-name associations with varying degrees of interference. The similarities and differences between these studies and the current results are outlined below.

The Heldmann et al. (2008) and Hammer et al. (2009) procedures included a self-elaboration component of using each errorless target word in a sentence. Hammer et al. (2009) explained that using the errorless words in a sentence ensured a comparable depth of word processing between errorless and errorful words, given that participants had to guess words in the errorful condition. This process was not carried out in the current study, and yet similar ERN findings are reported in both studies, suggesting that depth of word processing may not have a noticeable effect on ERN amplitude. Another important distinction from the current study is that Heldmann et al. (2008) taught errorless and errorful sessions 3-7 days apart, where as the current study (and apparently, Hammer et al. [2009]) utilized a single visit for both lear1ning conditions.

Some other key methodological differences between the current and previous errorless learning ERN research include the current study's use of an adaptive mean (rather than peak amplitude), averaging across several electrodes (rather than a single electrode), excluding omission trials from analyses (versus retaining them) and having a minimum number of error trials required in each condition (not reported in studies other than the current one). Each of these methodological elements alone or in combination could lead to differences in outcome, not to mention differences in number of sensors, segmentation windows, and other processing techniques.

Methodological differences aside, ERN findings from control participants in Hammer and colleagues (2009) are comparable with the current sample, while ERN amplitude findings for OCD participants were inconsistent with the ERN characteristics reviewed in the current study (as well as the authors' apriori hypotheses). Specifically, similar to the current study, Heldmann et al. (2008) found a benefit of errorless over errorful learning but "no impact of learning mode on the ERN amplitude" (p. 66). The authors explained this lack of effect within

the framework of the error likelihood model (ELM; Brown & Braver, 2005, 2007; Brown & Braver, 2008). However, another consideration in interpreting the lack of significant differences in ERN amplitude between groups and learning conditions (found currently and in other studies) pertains to the degree of interference or conflict present during word recognition. The degree of conflict present in a given task is relevant for interpreting ERN findings based on research support for the conflict monitoring theory (Carter & Van Veen, 2007; Larson, Clayson, & Clawson, 2014).

The conflict monitoring theory posits that the greater degree of conflict between response options, the greater the ACC activation which signals for increased attentional control to improve and/or maintain performance. Stimulus conflict refers to the degree of similarity between stimuli (making distinctions more difficult), while response conflict or "simultaneous activation of incompatible actions" (Danielmeier, Wessel, Steinhauser, & Ullsperger, 2009; Yeung & Cohen, 2006) can occur when a participant responds "no" to a word that he/she has previously seen and simultaneously recognizes that in fact the correct answer is "yes." Post-response conflict on error trials is reflected by the ERN, with greater conflict resulting in greater ERN amplitude (Danielmeier et al., 2009; Larson et al., 2014).

The degree of stimulus and response conflict in the current study consists of the following: 2-3 non-target words accompanied the oral presentation of a target word during each learning block of the errorful condition. During each computerized recognition block participants were presented with target words learned previously, non-target distractor words heard previously, and additional "random" distractor words not heard previously. Each target word and non-target distractor word began with the same first two letters, while the random distractor word did not. Consequently, each target word had a varying degree of potential

interference associated with its accurate discrimination/identification, and a corresponding degree of response conflict if an incorrect response was made. During learning trials, if participants correctly guessed the target errorful word on the first try (e.g., as more and more trials were completed) additional non-target words were provided by the experimenter in order to ensure the presence of distracters associated with the target word (e.g., "'broom' or 'brown' are other words you could have guessed, but 'bread' is correct"). Although this putatively served to maintain/generate stimulus and response conflict during recognition trials, a theoretically higher degree of conflict would have been elicited during recognition trials if participants were asked to generate their own alternative guesses following correct first responses (e.g., "'Bread' is correct. What other words start with 'BR'?" Even if groups in aim 2 are assumed to be more similar than different in terms of error processing (as hypothesized above) it is still unclear why ERN differences were not observed between learning conditions that theoretically differ in their degree of conflict.

In the current study, it was hypothesized that incorrect responses would result in greater conflict (ERN amplitude) during errorless trials than errorful trials. This was based on the evidence from previous research that errorless learning reduces interference from other non-target information that would normally be present following trial and error (or errorful) learning. Evidence for a relative decrease in conflict in the errorless condition was not clearly borne out by the current study. However, although there were no between-group differences, a significant inverse relationship between errorful ERN amplitude and errorful accuracy (but not errorless) was observed. This indicates that as accuracy increased, ERN amplitude became greater (i.e., more negative) and suggests that the better the performance, the greater the response conflict when a mistake was made.

Unexpected results were also reported by Hammer et al. (2013), who tested face-name associations with an errorless learning paradigm. In order to test the influence of varying degrees of interference/conflict on ERN amplitude, Hammer et al. (2013) examined errorless learning in comparison with two levels of errorful learning that differed with regard to the number of distractors introduced (1 vs. 2). Contrary to hypothesis, the authors found more prominent negative ERN amplitudes with the errorless condition and the 2 errorful distractors condition than with the single distractor errorful condition. That is, the lowest interference (errorless) and highest interference (2 distractors) conditions had similar ERN amplitudes, a result that is incongruent with the response conflict monitoring theory.

Although Hammer et al. (2013) did not take a position regarding what theory or model explained the ERN differences between conditions, there are some similarities in paradigm with the current study results. The condition in Hammer et al. (2013) that resulted in relatively reduced ERN amplitude was one in which target information was included along with a distracter name previously paired with a face (e.g., "this is not John") as well as a new name not previously introduced. This format of having target, distractor, and novel stimuli for each trial approximates the format of the current study. Hammer et al. (2013) opine that having to select 1 out of 3 different *types* of names (target, distractor, and new) may have led to a similar degree of response conflict between correct and incorrect responses, and thus an overall attenuation of ERN amplitude for that condition.

Of note is that there were not significant differences between the individuals with TBI and the control participants. Larson et al. (2007) reported attenuated ERN amplitude among severe TBI participants relative to controls, suggesting disrupted error processing, a result not replicated in the current study. Comparisons between the Larson et al. (2007) severe TBI sample

and the current M/S TBI sample indicate that the Larson et al. participants had considerably greater injury severity characteristics (>LOC and PTA, < GCS), and more recent injuries. It is possible that the current sample, while not "mild" in initial injury classification, more closely resembled participants outlined in other studies by Larson et al. (2012; 2011) who showed no between-groups differences in those with mild TBI and controls. The current study had several participants that were quite chronic (i.e., had a long time since their injury) and were functioning independently. Thus, they may have performed more similar to mild TBI participants. Of note, in this regard is that measures of cognitive functioning generally seemed comparable between the current and Larson et al. (2007) studies. Other published studies regarding error processing and acquired brain injury are inconsistent with the current study's lack of between-group ERN effect (Hogan, Vargha-Khadem, Saunders, Kirkham, & Baldeweg, 2006; Solbakk et al., 2014). Contradictory findings reviewed in this section are difficult to reconcile and confirm the importance of appropriate classification and assessment of symptoms and abilities, both clinically and in research settings (see Limitations below).

The current study's results also failed to replicate previous findings regarding affective differences in ERN amplitude and latency observed in previous studies (Larson, Fair, et al., 2011; Larson et al., 2009; Larson, Kaufman, et al., 2007). The error processing component of evaluative cognitive control has been previously shown to be disrupted in individuals with M/S TBI, with affective variables adversely impacting the ERN (Larson, Fair, et al., 2011; Larson et al., 2009; Larson, Kaufman, et al., 2007). Specifically, negative affect has been shown to be a better predictor of ERN amplitude than magnitude of cognitive dysfunction, injury severity, or time since injury (Larson, Fair, et al., 2011). Negative affect also reduces ERN amplitude in survivors of severe TBI (Larson et al., 2009). In the current study, variables of anxiety,

depression, and negative affect were not significantly correlated with ERN amplitude or latency, nor accuracy, regardless of learning condition. However, there were some significant behavioral findings pertaining to emotional functioning and performance which are reviewed above.

The implications for the current mixed results regarding the ERN (not) predicting accuracy suggest variability in patient groups, including variability within the same group or even the same sample (Larson, Clayson, et al., 2012; Larson, Farrer, et al., 2011), can influence outcomes. Depending upon specific tasks and measures applied, and differences in injury localization or cognitive efficiency, ERN characteristics will vary. Thus it appears that conflict monitoring and error processing indices in the current sample were not significantly different between groups.

**Limitations and Future Directions**

The current study should be considered within several limitations that may impact its research utility as well as generalizability to clinical practice. Although the current sample size of 28 (aim 1) is on par with or exceeds those of most errorless learning studies, a much larger sample would be ideal in order to better characterize the effects of errorless learning on TBI survivors. This is particularly true with regard to deciphering whether or to what degree of injury severity, memory impairment, or other cognitive factors influence outcome. Furthermore, the current sample was quite heterogeneous with regard to injury severity, chronicity, and mechanism. This variability in injury characteristics, combined with insufficient sample size and detailed medical records prohibited more detailed analyses that could better inform the literature regarding the potential efficacy of errorless learning with certain memory profiles, time since injury, or neuroanatomical localization of injury (which may have facilitated interpretation of aim 2). For example, it was common that when records were received, dozens of pages of

assessment and treatment information yielded extremely little quantitative data regarding injury severity and outcome. However, Lezak et al. (2012) point out that for indices of PTA for example (which was practically non-existent in medical records except for some notes stating simply, "patient is repetitive"), precise accuracy in measurement/tracking is unnecessary. Rather, macro-level estimates of PTA in hours and days are sufficient for clinical purposes. This approach of using hours for PTA was used in the current sample, including imputed duration of hours based on participant report of days wherein they were conscious but had no memory. Also of note is that a recent study reported that among abnormalities visualized on brain CT scans, GCS, and PTA estimates, only PTA was predictive of cognitive functioning 1 year post severe TBI (Sigurdardottir et al., 2015).

Future studies would be enhanced by collaborating with medical centers to establish the use of injury severity and orientation rating protocols at regular intervals that could inform injury classification at baseline. More importantly, advances in neuroimaging such as diffusion tensor imaging (DTI) have demonstrated advanced precision in evaluating and predicting outcome (Betz, Zhuo, Roy, Shanmuganathan, & Gullapalli, 2012; Galanaud et al., 2012; Matsushita, Hosoda, Naitoh, Yamashita, & Kohmura, 2011) and would be a key contribution in future studies to evaluate the long term changes associated with various cognitive rehabilitation methods.

The current study utilized a single training session, with no subsequent follow up. Consequently, inferences regarding the long-term retention of either errorless or errorful learning, or the effect of repeated sessions, are not possible from this sample. Within the session, participants attempted learning 15 words from the AVLT, 20 words from errorless condition, and 20 words from the errorful condition. In addition, there was a distractor list for the AVLT and

distractor words introduced during the errorful trials. Consequently, during the ~3hour experiment participants were exposed to a substantial number of target and non-target words in a memorization context. This may have interfered with the effective retention and appropriate exclusion of information (i.e. greater overall conflict/interference), or could have served to reduce response conflict due to reduced motivation and/or fatigue. There was a significant effect of session # on accuracy for TBI participants, indicating that regardless of learning condition, TBI participants' performance declined over time. Subjectively, TBI participants appeared and reported feeling tired following the experiment more than controls. Future studies should schedule learning sessions on separate days (preferably separated by several days) to control for the degree of fatigue that accompanies an extended period of mental exertion.

Of note in the interpretation of regression analyses is that because the majority of participants from both groups performed well, there is likely a restriction of range in variance. Thus, regressions may only be predicting a narrow band of participant performance that could increase the weight of any single case or lead to statistically significant effects that are not clinically meaningful. One factor to consider in this regard is that the task may not have been sufficiently challenging for either group to produce the degree of response variability necessary to reduce restriction of range.

With regard to the second aim, one problem inherent with traditional EEG is separating out the background "noise" that is present within a particular component of interest. This noise may be correlated with the component of interest, or involve other semi-random EEG activity. In order to control for the noise that is recorded together with an ERP signal (as well as subtle differences in latency and amplitude), averaging and filtering methods are necessary to provide a higher signal-to-noise ratio (Spencer, 2005). Previous research has demonstrated that as few as

6-8 error trials are necessary for a reliable ERN (Olvet & Hajcak, 2009; Pontifex et al., 2010) while others report 13-14 trials at a minimum are necessary (Baldwin et al., 2015; Larson, Baldwin, Good, & Fair, 2010). Baldwin et al. (2015) reported that within-person variability was greater than between-person across pathologies and waveforms analyzed and suggested that more trials may be necessary for reliability in clinical samples than for healthy controls. In order to maintain an appropriate signal to noise ratio and maintain an adequate number of trials for analyzing the ERN while still preserving a reasonable sample size, the current study was less conservative, using 6 error trials as the lower limit. Although this provided "clean" data to work with and conduct analyses, it also had the effect of reducing meaningful variability of performance (13 participants [7 TBI, 6 Control] were excluded from aim 2).

In summary, considerable variability exists across and within clinical groups with regard to the efficacy of errorless learning, as well as variability within and between EEG studies of conflict monitoring and TBI. Consequently, inferences regarding the potential comparability of patient groups (or symptom severity), efficacy of a given intervention, and meaning of an ERP should be backed by extensive data gathered from the individual(s) in question. As one example illustrates, Yeung and Cohen (2006) reported that reductions in stimulus presentation and attentional inputs in a computational model of conflict monitoring resulted in significant reductions in ERN amplitude. Future TBI learning studies would be improved by including measures of visual attention and vigilance (e.g., visual discrimination, visual copy, and visual memory subtests, and a continuous performance test) to inform the likely impact of visual attention and concentration on error processing during acquisition and recognition trials. Detailed reporting of methods and the context wherein it was applied facilitates understanding and replicability. One example of a potential point of difficulty that has or could arise if these

principles are overlooked is well-meaning clinicians or teachers applying errorless learning methods indiscriminately to populations or with tasks that are not proper candidates for the intervention.

## Summary and Conclusion

The prevalence of M/S TBI in the United States and across the world continues to be a significant problem, as are the many challenges of treatment and care (Chua et al., 2007). The deficits experienced by survivors of M/S TBI are substantial, and impact error processing. Errorless learning has demonstrated efficacy in several clinical populations but research has not been previously published using a M/S TBI sample. The primary goal (aim 1) of the current study was to evaluate the efficacy of a brief session of errorless learning compared to errorful learning in a group of M/S TBI survivors and demographically-similar controls. Results from aim 1 indicated that survivors of M/S TBI were slower across both errorless and errorful conditions, while both groups had significantly faster reaction times in the errorless condition. There was not a statistically significant main effect of learning condition ($p = .07$) or group ($p = .06$) on accuracy, and no Group x Condition x Accuracy interaction ($p = .33$). Indices of memory and executive functioning, and group membership (TBI or Control) were used in regression models to predict accuracy. These models were significantly predictive of both errorless and errorful accuracy ($ps < .01$), with memory functioning being a significant independent predictor of errorless but not errorful accuracy. Measures of negative affect indicated that PANAS negative scores were independently predictive of accuracy in the errorful condition, although other measures of affect did not appear to be significantly related to outcomes.

Considering the widespread use of errorless learning for the rehabilitation of cognitively-impaired individuals, better understanding of the neural processes underlying this training method was also considered valuable in order to advance clinical rehabilitation outcomes. The error processing component of evaluative cognitive control, the ERN, has been previously shown to be disrupted in individuals with M/S TBI, with affective variables negatively impacting the ERN as well (Larson, Fair, et al., 2011; Larson et al., 2009; Larson, Kaufman, et al., 2007). Aim 2 of the current study was to investigate the neural time course of errorless learning in participants with M/S TBI by analyzing ERN amplitude and latency. However, conclusions as to the role of the ERN in the current study were difficult to make. Results from aim 2 indicated the presence of a reliable ERN across conditions, although there were no main effects of Condition, Group, or Group x Condition interactions on ERN amplitude and latency ($ps \geq .22$). Null results were also observed for ERN latency ($ps \geq 0.33$). ERN latency was not predictive of accuracy for either condition ($ps \geq .08$). Group was a significant independent predictor of accuracy in the errorless condition ($p = .05$), but not the errorful condition ($p = .45$). It was hoped that the current study would sufficiently address and clarify the role of neural processes in M/S TBI rehabilitation, but further research is needed to adequately address this issue.

The current study serves to tentatively support the efficacy of errorless learning in a M/S TBI sample while encouraging further research as to its efficacy or how errorless learning can be better applied. However, several key questions still need to be addressed, including the role of cognitive control, injury severity variables, and the cognitive processes required to benefit from errorless learning. Proposed studies of interest that will help clarify the utility of errorless learning in clinical populations include trial and error vs. errorless learning of daily living tasks in Alzheimer's patients (Voigt-Radloff, Leonhart, Rikkert, Kessels, & Hull, 2011), and using

errorless vs. trial and error learning with goal management training for patients with acquired brain injury (Bertens, Fasotti, Boelen, & Kessels, 2013). These proposed studies with large sample sizes will be key in clarifying the current state of cognitive rehabilitation methods in clinical populations. Given the substantial difficulties associated with M/S TBI, continual improvement of intervention methods via corresponding research is critical.

References

Akhtar, S., Moulin, C. J. A., & Bowie, P. C. W. (2006). Are people with mild cognitive impairment aware of the benefits of errorless learning? *Neuropsychological Rehabilitation, 16*(3), 329-346.

Baddeley, A., & Wilson, B. A. (1994). When implicit learning fails: Amnesia and the problem of error elimination. *Neuropsychologia, 32*(1), 53-68.

Baldwin, S. A., Larson, M. J., & Clayson, P. E. (2015). The dependability of electrophysiological measurements of performance monitoring in a clinical sample: A generalizability and decision analysis of the ERN and Pe. *Psychophysiology*. doi: 10.1111/psyp.12401

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

Bertens, D., Fasotti, L., Boelen, D. H., & Kessels, R. P. (2013). A randomized controlled trial on errorless learning in goal management training: Study rationale and protocol. *BMC Neurology, 13*, 64. doi: 10.1186/1471-2377-13-64

Betz, J., Zhuo, J., Roy, A., Shanmuganathan, K., & Gullapalli, R. P. (2012). Prognostic value of diffusion tensor imaging parameters in severe traumatic brain injury. *Journal of Neurotrauma, 29*(7), 1292-1305. doi: 10.1089/neu.2011.2215

Bigler, E. D. (1990). Neuropathology of traumatic brain injury. In E. D. Bigler (Ed.), *Traumatic brain injury* (pp. 13-49). Austin, TX: Pro-ed.

Bigler, E. D. (2009). Traumatic brain injury. In M. F. Weiner & A. M. Lipton (Eds.), *The American Psychiatric Publishing textbook of Alzheimer disease and other dementias.* (pp. 229-246). Arlington, VA: American Psychiatric Publishing, Inc.

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.

Bond, M. R. (1986). Neurobehavioral sequelae of closed head injury. In I. Grant & K. M. Adams (Eds.), *Neuropsychological assessment of neuropsychological disorders* (pp. 347-373). New York: Oxford University Press.

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

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.

Braver, T. S., Barch, D. M., & Cohen, J. D. (1999). Cognition and control in schizophrenia: A computational model of dopamine and prefrontal function. *Biological Psychiatry, 46*(3), 312-328.

Brown, J. W., & Braver, T. S. (2005). Learned predictions of error likelihood in the anterior cingulate cortex. *Science, 307*(5712), 1118-1121.

Brown, J. W., & Braver, T. S. (2007). Risk prediction and aversion by anterior cingulate cortex. *Cognitive, Affective & Behavioral Neuroscience, 7*(4), 266-277. doi: 10.3758/cabn.7.4.266

Brown, J. W., & Braver, T. S. (2008). A computational model of risk, conflict, and individual difference effects in the anterior cingulate cortex. *Brain Research, 1202*, 99-108. doi: 10.1016/j.brainres.2007.06.080

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.

Bush, G., Luu, P., & Posner, M. I. (2000). Cognitive and emotional influences in anterior cingulate cortex. *Trends in Cognitive Sciences, 4*(6), 215-222. doi: 10.1016/s1364-6613(00)01483-2

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.

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, 97*(4), 1944-1948.

Carter, C. S., & Van Veen, V. (2007). Anterior cingulate cortex and conflict detection: An update of theory and data. *Cognitive, Affective & Behavioral Neuroscience, 7*(4), 367-379. doi: 10.3758/cabn.7.4.367

Chua, K. S. G., Ng, Y.-S., Yap, S. G. M., & Bok, C.-W. (2007). A brief review of Traumatic Brain Injury rehabilitation. *Annals of the Academy of Medicine, 36*, 31-42.

Clare, L., & Jones, R. S. (2008). Errorless learning in the rehabilitation of memory impairment: A critical review. *Neuropsychology Review, 18*(1), 1-23. doi: 10.1007/s11065-008-9051-4

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

Clayson, P. E., & Larson, M. J. (2012). Cognitive performance and electrophysiological indices of cognitive control: A validation study of conflict adaptation. *Psychophysiology, 49*(5), 627-637. doi: 10.1111/j.1469-8986.2011.01345.x

Cohen, J. D., & Servan-Schreiber, D. (1992). Context, cortex, and dopamine: A connectionist approach to behavior and biology in schizophrenia. *Psychological Review, 99*(1), 45-77.

Conrad, N., Doering, B. K., Rief, W., & Exner, C. (2010). Looking beyond the importance of life goals. The personal goal model of subjective well-being in neuropsychological rehabilitation. *Clinical Rehabilitation, 24*(5), 431-443. doi: 10.1177/0269215509358930

Coons, S. J., Rao, S., Keininger, D. L., & Hays, R. D. (2000). A comparative review of generic quality-of-life instruments. *Pharmacoeconomics, 17*(1), 13-35.

Coronado, V. G., Xu, L., Basavaraju, S. V., McGuire, L. C., Wald, M. M., Faul, M. D., . . . Hemphill, J. D. (2011). Surveillance for traumatic brain injury-related deaths--United States, 1997-2007. *Morbidity and Mortality Weekly Report Surveillance Summaries, 60*(5), 1-32.

Crawford, J. R., & Henry, J. D. (2004). The Positive and Negative Affect Schedule (PANAS): Construct validity, measurement properties and normative data in a large non-clinical sample. *British Journal of Clinical Psychology, 43*, 245–265.

Crawford, J. R., Henry, J. D., Crombie, C., & Taylor, E. P. (2001). Brief report: Normative data for the HADS from a large non-clinical sample. *British Journal of Clinical Psychology, 40*, 429-434.

Cyr, A. A., & Anderson, N. D. (2012). Trial-and-error learning improves source memory among young and older adults. *Psychology and Aging, 27*(2), 429-439. doi: 10.1037/a0025115

Danielmeier, C., Wessel, J. R., Steinhauser, M., & Ullsperger, M. (2009). Modulation of the error-related negativity by response conflict. *Psychophysiology, 46*(6), 1288-1298. doi: 10.1111/j.1469-8986.2009.00860.x

de Werd, M. M., Boelen, D., Rikkert, M. G., & Kessels, R. P. (2013). Errorless learning of everyday tasks in people with dementia. *Journal of Clinical Interventions in Aging, 8*, 1177-1190. doi: 10.2147/cia.s46809

Dechamps, A., Fasotti, L., Jungheim, J., Leone, E., Dood, E., Allioux, A., . . . Kessels, R. P. (2011). Effects of different learning methods for instrumental activities of daily living in patients with Alzheimer's dementia: A pilot study. *American Journal of Alzheimer's Disease and Other Dementias, 26*(4), 273-281. doi: 10.1177/1533317511404394

Dehaene, S., Posner, M. I., & Tucker, D. M. (1994). Localization of a neural system for error detection and compensation. *Psychological Science, 5*(5), 303-305. doi: 10.1111/j.1467-9280.1994.tb00630.x

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

Dien, J. (2010). The ERP PCA Toolkit: An open source program for advanced statistical analysis of event-related potential data. *Journal of Neuroscience Methods, 187*(1), 138-145. doi: 10.1016/j.jneumeth.2009.12.009

Dien, J., Franklin, M. S., & May, C. J. (2006). Is "Blank" a suitable neutral prime for event-related potential experiments? *Brain and Language, 97*(1), 91-101. doi: 10.1016/j.bandl.2005.08.002

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

Dijkers, M. P. (2004). Quality of life after traumatic brain injury: A review of research approaches and findings. *Archives of Physical Medicine Rehabilitation, 85*(4 Suppl 2), S21-35.

Dikmen, S. S., Machamer, J. E., Powell, J. M., & Temkin, N. R. (2003). Outcome 3 to 5 years after moderate to severe traumatic brain injury. *Archives of Physical Medicine Rehabilitation, 84*(10), 1449-1457.

Dou, Z. L., Man, D. W. K., Ou, H. N., Zheng, J. L., & Tam, S. F. (2006). Computerized errorless learning-based memory rehabilitation for Chinese patients with brain injury: A preliminary quasi-experimental clinical design study. *Brain Injury, 20*(3), 219-225.

Dunn, J., & Clare, L. (2007). Learning face-name associations in early-stage dementia: Comparing the effects of errorless learning and effortful processing. *Neuropsychological Rehabilitation, 17*(6), 735-754. doi: 10.1080/09602010701218317

Emerson, C. S., Harrison, D. W., Everhart, D. E., & Williamson, J. B. ( 2001). Grip strength assymetry in depressed boys. *Neuropsychiatry, Neuropsychology, and Behavioral Neurology, 14*, 130-134.

Emerson, C. S., Mollet, G. A., & Harrison, D. W. (2005). Anxious-depression in boys: An evaluation of executive functioning. *Archives of Clinical Neuropsychology, 20*, 539-546.

Evans, J. J., Wilson, B. A., Schuri, U., Andrade, J., Baddeley, A., Bruna, O., . . . Taussik, I. (2000). A comparison of 'errorless' and 'trial-and-error' learning methods for teaching

individuals with acquired memory deficits. *Neuropsychological Rehabilitation, 10*(1), 67-101.

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.

Findler, M., Cantor, J., Haddad, L., Gordon, W., & Ashman, T. (2001). The reliability and validity of the SF-36 health survey questionnaire for use with individuals with traumatic brain injury. *Brain Injury, 15*(8), 715-723. doi: 10.1080/02699050010013941

Frost, R. B., Farrer, T. J., Primosch, M., & Hedges, D. W. (2013). Prevalence of traumatic brain injury in the general adult population: A meta-analysis. *Neuroepidemiology, 40*(3), 154-159. doi: 10.1159/000343275

Galanaud, D., Perlbarg, V., Gupta, R., Stevens, R. D., Sanchez, P., Tollard, E., . . . Puybasset, L. (2012). Assessment of white matter injury and outcome in severe brain trauma: A prospective multicenter cohort. *Anesthesiology, 117*(6), 1300-1310. doi: 10.1097/ALN.0b013e3182755558

Gale, S. D., & Hopkins, R. O. (2004). Effects of hypoxia on the brain: Neuroimaging and neuropsychological findings following carbon monoxide poisoning and obstructive sleep apnea. *Journal of the International Neuropsychological Society, 10*(1), 60-71. doi: 10.1017/s1355617704101082

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.

Gerstenbrand, F., & Stepan, C. H. (2001). Mild traumatic brain injury. *Brain Injury, 15*, 95-97.

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: Demographic corrections for age, education, and ethnicity. *Assessment, 6*(2), 147-178.

Glisky, E. L. (1995). Acqusition and transfer of word processing skill by an amnesic patient. *Neuropsychological Rehabilitation, 5*(4), 299-318. doi: 10.1080/09602019508401474

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

Guild, E. B., & Anderson, N. D. (2012). Self-generation amplifies the errorless learning effect in healthy older adults when transfer appropriate processing conditions are met. *Aging, Neuropsychology and Cognition, 19*(5), 592-607. doi: 10.1080/13825585.2011.639869

Guillery-Girard, B., Martins, S., Parisot-Carbuccia, D., & Eustache, F. (2004). Semantic acquisition in childhood amnesic syndrome: A prospective study. *Neuroreport, 15*(2), 377-381.

Hammer, A., Heldmann, M., & Munte, T. F. (2013). Errorless and errorful learning of face-name associations: An electrophysiological study. *Biological Psychology, 92*(2), 169-178. doi: 10.1016/j.biopsycho.2012.11.003

Hammer, A., Kordon, A., Heldmann, M., Zurowski, B., & Münte, T. F. (2009). Brain potentials of conflict and error-likelihood following errorful and errorless learning in Obsessive-Compulsive Disorder. *PLoS ONE, 4*(8), e6553.

Hammer, A., Mohammadi, B., Schmicker, M., Saliger, S., & Munte, T. F. (2011). Errorless and errorful learning modulated by transcranial direct current stimulation. *BMC Neuroscience, 12*, 72. doi: 10.1186/1471-2202-12-72

Hammer, A., Tempelmann, C., & Munte, T. F. (2013). Recognition of face-name associations after errorless and errorful learning: An fMRI study. *BMC Neuroscience, 14*, 30. doi: 10.1186/1471-2202-14-30

Haslam, C., Bazen-Peters, C., & Wright, I. (2012). Errorless learning improves memory performance in children with acquired brain injury: A controlled comparison of standard and self-generation techniques. *Neuropsychological Rehabilitation, 22*(5), 697-715. doi: 10.1080/09602011.2012.686820

Haslam, C., Hodder, K. I., & Yates, P. J. (2011). Errorless learning and spaced retrieval: How do these methods fare in healthy and clinical populations? *Journal of Clinical and Experimental Neuropsychology, 33*(4), 432-447. doi: 10.1080/13803395.2010.533155

Haslam, C., Moss, Z., & Hodder, K. (2010). Are two methods better than one? Evaluating the effectiveness of combining errorless learning with vanishing cues. *Journal of Clinical and Experimental Neuropsychology, 32*(9), 973-985. doi: 10.1080/13803391003662686

Heldmann, M., Markgraf, U., Rodríguez-Fornells, A., & Münte, T. F. (2008). Brain potentials reveal the role of conflict in human errorful and errorless learning. *Neuroscience Letters, 444*(1), 64-68.

Hogan, A. M., Vargha-Khadem, F., Saunders, D. E., Kirkham, F. J., & Baldeweg, T. (2006). Impact of frontal white matter lesions on performance monitoring: ERP evidence for cortical disconnection. *Brain, 129*(8), 2177-2188. doi: 10.1093/brain/awl160

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*(4), 679-709. doi: 10.1037/0033-295x.109.4.679

Holroyd, C. B., Larsen, J. T., & Cohen, J. D. (2004). Context dependence of the event-related brain potential associated with reward and punishment. *Psychophysiology, 41*(2), 245-253. doi: 10.1111/j.1469-8986.2004.00152.x

Huffmeijer, R., Bakermans-Kranenburg, M. J., Alink, L. R., & van Ijzendoorn, M. H. (2014). Reliability of event-related potentials: The influence of number of trials and electrodes. *Physiol Behav, 130*, 13-22. doi: 10.1016/j.physbeh.2014.03.008

Jean, L., Simard, M., Wiederkehr, S., Bergeron, M. E., Turgeon, Y., Hudon, C., . . . van Reekum, R. (2010). Efficacy of a cognitive training programme for mild cognitive impairment: Results of a randomised controlled study. *Neuropsychological Rehabilitation, 20*(3), 377-405. doi: 10.1080/09602010903343012

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.

Jorge, R. E., Robinson, R. G., Moser, D., Tateno, A., Crespo-Facorro, B., & Arndt, S. (2004). Major depression following traumatic brain injury. *Archives of General Psychiatry, 61*, 42-50.

Kessels, R. P., & de Haan, E. H. (2003). Implicit learning in memory rehabilitation: A meta-analysis on errorless learning and vanishing cues methods. *Journal of Clinical and Experimental Neuropsychology, 25*(6), 805-814.

Kessels, R. P., & Hensken, L. M. (2009). Effects of errorless skill learning in people with mild-to-moderate or severe dementia: A randomized controlled pilot study. *NeuroRehabilitation, 25*(4), 307-312. doi: 10.3233/nre-2009-0529

King, N. S., Crawford, S., Wenden, F. J., Moss, N. E., Wade, D. T., & Caldwell, F. E. (1997). Measurement of post-traumatic amnesia: How reliable is it? *Journal of Neurology, Neurosurgery and Psychiatry, 62*(1), 38-42.

Kixmiller, J. S. (2002). Evaluation of prospective memory training for individuals with mild Alzheimer's disease. *Brain and Cognition, 49*(2), 237-241.

Laffan, A. J., Metzler-Baddeley, C., Walker, I., & Jones, R. W. (2010). Making errorless learning more active: Self-generation in an error free learning context is superior to standard errorless learning of face-name associations in people with Alzheimer's disease. *Neuropsychological Rehabilitation, 20*(2), 197-211. doi: 10.1080/09602010903202432

Landis, J., Hanten, G., Levin, H. S., Li, X., Ewing-Cobbs, L., Duron, J., & High, W. M., Jr. (2006). Evaluation of the errorless learning technique in children with traumatic brain injury. *Archives of Physical Medicine Rehabilitation, 87*(6), 799-805. doi: 10.1016/j.apmr.2006.02.017

Langlois, J. A., Rutland-Brown, W., & Wald, M. M. (2006). The epidemiology and impact of traumatic brain injury: A brief overview. *Journal of Head Trauma Rehabilitation, 21*(5), 375-378.

Larson, M. J., Baldwin, S. A., Good, D. A., & Fair, J. E. (2010). 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., Clawson, A., Clayson, P. E., & South, M. (2012). Cognitive control and conflict adaptation similarities in children and adults. *Developmental Neuropsychology, 37*(4), 343-357. doi: 10.1080/87565641.2011.650337

Larson, M. J., Clayson, P. E., & Clawson, A. (2014). Making sense of all the conflict: A theoretical review and critique of conflict-related ERPs. *International Journal of Psychophysiology, 93*(3), 283-297. doi: 10.1016/j.ijpsycho.2014.06.007

Larson, M. J., Clayson, P. E., & Farrer, T. J. (2012). Performance monitoring and cognitive control in individuals with mild traumatic brain injury. *Journal of the International Neuropsychological Society, 18*(2), 323-333. doi: 10.1017/s1355617711001779

Larson, M. J., Fair, J. E., Farrer, T. J., & Perlstein, W. M. (2011). Predictors of performance monitoring abilities following traumatic brain injury: The influence of negative affect and cognitive sequelae. *International Journal of Psychophysiology, 82*(1), 61-68. doi: 10.1016/j.ijpsycho.2011.02.001

Larson, M. J., Farrer, T. J., & Clayson, P. E. (2011). Cognitive control in mild traumatic brain injury: Conflict monitoring and conflict adaptation. *International Journal of Psychophysiology, 82*(1), 69-78. doi: 10.1016/j.ijpsycho.2011.02.018

Larson, M. J., Kaufman, D. A., Kellison, I. L., Schmalfuss, I. M., & Perlstein, W. M. (2009). Double jeopardy! The additive consequences of negative affect on performance-monitoring decrements following traumatic brain injury. *Neuropsychology, 23*(4), 433-444. doi: 10.1037/a0015723

Larson, M. J., Kaufman, D. A., 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., Perlstein, W. M., Demery, J. A., & Stigge-Kaufman, D. A. (2006). Cognitive control impairments in traumatic brain injury. *Journal of Clinical and Experimental Neuropsychology, 28*(6), 968-986. doi: 10.1080/13803390600646860

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

Larson, M. J., Weaver, L. K., & Hopkins, R. O. (2007). Cognitive sequelae in acute respiratory distress syndrome patients with and without recall of the intensive care unit. *Journal of the International Neuropsychological Society, 13*(4), 595-605. doi: 10.1017/s1355617707070749

Leon-Carrion, J., Dominguez-Morales, M. R., Barroso y Martin, J. M., & Leon-Dominguez, U. (2012). Recovery of cognitive function during comprehensive rehabilitation after severe traumatic brain injury. *Journal of Rehabilitation Medicine, 44*(6), 505-511. doi: 10.2340/16501977-0982

Levine, B., Katz, D. I., Dade, L., & Black, S. E. (2002). Novel approaches to the assessment of frontal damage and executive deficits in traumatic brain injury. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 448-465). New York: Oxford University Press.

Lezak, M. D., Howieson, D., Bigler, E. D., & Tranel, D. (2012). *Neuropsychological assessment* (5th ed.). New York: Oxford Press.

Lloyd, J., Riley, G. A., & Powell, T. E. (2009). Errorless learning of novel routes through a virtual town in people with acquired brain injury. *Neuropsychological Rehabilitation, 19*(1), 98-109.

Lubinsky, T., Rich, J. B., & Anderson, N. D. (2009). Errorless learning and elaborative self-generation in healthy older adults and individuals with amnestic mild cognitive

impairment: Mnemonic benefits and mechanisms. *Journal of the International Neuropsychological Society, 15*(5), 704-716. doi: 10.1017/s1355617709990270

Man, D. W., Lee, E. W., Tong, E. C., Yip, S. C., Lui, W. F., & Lam, C. S. (2004). Health services needs and quality of life assessment of individuals with brain injuries: A pilot cross-sectional study. *Brain Injury, 18*(6), 577-591. doi: 10.1080/02699050310001646143

Maruish, M., & DeRosa, M. A. (2009). *A guide to the integration of certified Short Form survey scoring and data quality evaluation capabilities.* Lincoln, RI: QualityMetric Incorporated.

Matsushita, M., Hosoda, K., Naitoh, Y., Yamashita, H., & Kohmura, E. (2011). Utility of diffusion tensor imaging in the acute stage of mild to moderate traumatic brain injury for detecting white matter lesions and predicting long-term cognitive function in adults. *Journal of Neurosurgery, 115*(1), 130-139. doi: 10.3171/2011.2.jns101547

McMillan, T. M., Jongen, E. L., & Greenwood, R. J. (1996). Assessment of post-traumatic amnesia after severe closed head injury: Retrospective or prospective? *Journal of Neurology, Neurosurgery, and Psychiatry, 60*(4), 422-427.

Mialet, J. P., Pope, H. G., & Yurgelun-Todd, D. (1996). Impaired attention in depressive states: A non-specific deficit? *Psychological Medicine, 26*, 1009-1020.

Middleton, E. L., & Schwartz, M. F. (2012). Errorless learning in cognitive rehabilitation: A critical review. *Neuropsychological Rehabilitation, 22*(2), 138-168. doi: 10.1080/09602011.2011.639619

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex. *Annual Review of Neuroscience, 24*, 167-202.

Millis, S. R., Rosenthal, M., Novack, T. A., Sherer, M., Nick, T. G., Kreutzer, J. S., . . . Ricker, J. H. (2001). Long-term neuropsychological outcome after traumatic brain injury. *Journal of Head Trauma Rehabilitation, 16*(4), 343-355.

Mitrushina, M., Boone, K. B., Razani, J., & D'Elia, L. F. (2005). *Handbook of normative data for neuropsychological assessment* (2nd ed.): Oxford University Press.

Mount, J., Pierce, S. R., Parker, J., DiEgidio, R., Woessner, R., & Spiegel, L. (2007). Trial and error versus errorless learning of functional skills in patients with acute stroke. *NeuroRehabilitation, 22*(2), 123-132.

Murphy, M. P., & Carmine, H. (2012). Long-term health implications of individuals with TBI: A rehabilitation perspective. *NeuroRehabilitation, 31*(1), 85-94. doi: 10.3233/nre-2012-0777

Myers, T. A. (2011). Goodbye, listwise deletion: Presenting hot deck imputation as an easy and effective tool for handling missing data. *Communication Methods and Measures, 5*, 297-310.

Noonan, K. A., Pryer, L. R., Jones, R. W., Burns, A. S., & Lambon Ralph, M. A. (2012). A direct comparison of errorless and errorful therapy for object name relearning in Alzheimer's disease. *Neuropsychological Rehabilitation, 22*(2), 215-234. doi: 10.1080/09602011.2012.655002

Olvet, D. M., & Hajcak, G. (2008). The error-related negativity (ERN) and psychopathology: Toward an endophenotype. *Clinical Psychology Review, 28*(8), 1343-1354. doi: 10.1016/j.cpr.2008.07.003

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

Page, M., Wilson, B. A., Shiel, A., Carter, G., & Norris, D. (2006). What is the locus of the errorless-learning advantage? *Neuropsychologia, 44*(1), 90-100. doi: 10.1016/j.neuropsychologia.2005.04.004

Perlstein, W. M., Cole, M. A., Demery, J., Seignourel, P. J., Dixit, N. K., Larson, M. J., & Briggs, R. W. (2004). Parametric manipulation of working memory load in traumatic brain injury: Behavioral and neural correlates. *Journal of the International Neuropsychological Society, 10*, 724-741.

Perlstein, W. M., Larson, M. J., Dotson, V. M., & Kelly, K. G. (2006). Temporal dissociation of components of cognitive control dysfunction in severe TBI: ERPs and the cued-Stroop task. *Neuropsychologia, 44*(2), 260-274.

Pitel, A. L., Beaunieux, H., Lebaron, N., Joyeux, F., Desgranges, B., & Eustache, F. (2006). Two case studies in the application of errorless learning techniques in memory impaired patients with additional executive deficits. *Brain Injury, 20*(10), 1099-1110.

Plassman, B. L., Havlik, R. J., Steffens, D. C., Helms, M. J., Newman, T. N., Drosdick, D., . . . Breitner, J. C. (2000). Documented head injury in early adulthood and risk of Alzheimer's disease and other dementias. *Neurology, 55*(8), 1158-1166.

Pontifex, M. B., Scudder, M. R., Brown, M. L., O'Leary, K. C., Wu, C. T., Themanson, J. R., & Hillman, C. H. (2010). On the number of trials necessary for stabilization of error-related brain activity across the life span. *Psychophysiology, 47*(4), 767-773. doi: 10.1111/j.1469-8986.2010.00974.x

Prigatano, G. P. (1999). Commentary: Beyond statistics and research design. *Journal of Head Trauma Rehabilitation, 14*, 308-311.

Prigatano, G. P. (2005). Therapy for emotional and motivational disorders In W. M. High, A. M. Sander & M. A. Struchen (Eds.), *Rehabilitation for traumatic brain injury* (pp. 383). New York: Oxford University Press.

Prigatano, G. P. (2008). NeuropsychologicaI rehabilitation and psychodynamic psychotherapy. In J. E. Morgan & J. H. Ricker (Eds.), *Textbook of clinical neuropsychology* (pp. 985-995). New York: Taylor and Francis.

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

Ridderinkhof, K. R., van den Wildenberg, W. P. M., Segalowitz, S. J., & Carter, C. S. (2004). Neurocognitive mechanisms of cognitive control: The role of prefrontal cortex in action selection, response inhibition, performance monitoring, and reward-based learning. *Brain and Cognition, 56*(2), 129-140. doi: 10.1016/j.bandc.2004.09.016

Rodriguez-Fornells, A., Kofidis, C., & Münte, T. F. (2004). An electrophysiological study of errorless learning. *Cognitive Brain Research, 19*(2), 160-173.

Rohling, M. L., Faust, M. E., Beverly, B., & Demakis, G. (2009). Effectiveness of cognitive rehabilitation following acquired brain injury: A meta-analytic re-examination of Cicerone et al.'s (2000, 2005) systematic reviews. *Neuropsychology, 23*(1), 20-39. doi: 10.1037/a0013659

Ruis, C., & Kessels, R. P. (2005). Effects of errorless and errorful face-name associative learning in moderate to severe dementia. *Aging Clinical and Experimental Research, 17*(6), 514-517.

Scheibel, R. S., Newsome, M. R., Steinberg, J. L., Pearson, D. A., Rauch, R. A., Mao, H., . . . Levin, H. S. (2007). Altered brain activation during cognitive control in patients with

moderate to severe traumatic brain injury. *Neurorehabilitation and Neural Repair, 21*, 36-45.

Scheibel, R. S., Pearson, D. A., Faria, L. P., Kotrla, K. J., Aylward, E., Bachevalier, J., & Levin, H. S. (2003). An fMRI study of executive functioning after severe diffuse TBI. *Brain Injury, 17*, 919-930.

Schmidt, M. (1996). *Rey Auditory Verbal Learning Test: A handbook*. Los Angeles, CA: Western Psychological Services.

Schneider, W., Eschmann, A., & Zuccolotto, A. (2002). *E-Prime user's guide.* Pittsburgh, PA: Psychology Software Tools, Inc.

Seignourel, P. J., Robins, D. L., Larson, M. J., Demery, J. A., Cole, M. A., & Perlstein, W. M. (2005). Cognitive control in closed head injury: Context maintenance dysfunction or prepotent response inhibition deficit? *Neuropsychology, 19*(5), 578-590.

Shenal, B. V., Harrison, D. W., & Demaree, H. A. ( 2003). Neuropsychology of depression: A literature review and preliminary model. *Neuropsychology Review, 13*, 33-42.

Sigurdardottir, S., Andelic, N., Wehling, E., Roe, C., Anke, A., Skandsen, T., . . . Schanke, A. K. (2015). Neuropsychological functioning in a national cohort of severe traumatic brain injury: Demographic and acute injury-related predictors. *Journal of Head Trauma Rehabilitation, 30*(2), E1-12. doi: 10.1097/htr.0000000000000039

Silver, J. M., Kramer, R., Greenwald, S., & Weissman, M. (2001). The association between head injuries and psychiatric disorders: Findings from the New Haven NIMH Epidemiologic Catchment Area Study. *Brain Injury, 15*, 935-945.

Sohlberg, M. M., & Mateer, C. A. (2001). *Cognitive rehabilitation: An integrative neuropsychological approach*. New York: The Guilford Press.

Solbakk, A. K., Funderud, I., Lovstad, M., Endestad, T., Meling, T., Lindgren, M., . . . Kramer, U. M. (2014). Impact of orbitofrontal lesions on electrophysiological signals in a stop signal task. *Journal of Cognitive Neuroscience, 26*(7), 1528-1545. doi: 10.1162/jocn_a_00561

Sozda, C. N., Larson, M. J., Kaufman, D. A., Schmalfuss, I. M., & Perlstein, W. M. (2011). Error-related processing following severe traumatic brain injury: An event-related functional magnetic resonance imaging (fMRI) study. *International Journal of Psychophysiology, 82*(1), 97-106. doi: 10.1016/j.ijpsycho.2011.06.019

Spencer, K. M. (2005). Averaging, detection, and classification of ERPs. In T. C. Handy (Ed.), *Event-related potentials: A methods handbook* (pp. 209-227). Cambridge: MIT Press.

Starkstein, S. E., & Jorge, R. E. (2005). Dementia after traumatic brain injury. *International Psychogeriatrics, 17*, S93-S107. doi: 10.1017/s1041610205001973

Strangman, G., O'Neil-Pirozzi, T. M., Burke, D., Cristina, D., Goldstein, R., Rauch, S. L., . . . Glenn, M. B. (2005). Functional neuroimaging and cognitive rehabilitation for people with traumatic brain injury. *American Journal Of Physical Medicine & Rehabilitation, 84*, 62-75. doi: 0894-9115

Strauss, E., Sherman, E., & Spreen, O. (2006). *A compendium of neuropsychological tests: Administration, norms, and commentary* (3rd ed.). New York: Oxford University Press.

Sweeney, J. A., Kmiec, J. A., & Kupfer, D. J. (2000). Neuropsychologic impairments in bipolar and unipolar mood disorders on the CANTAB neurocognitive battery. *Biological Psychiatry, 48*, 678-684.

Tailby, R., & Haslam, C. (2003). An investigation of errorless learning in memory-impaired patients: Improving the technique and clarifying theory. *Neuropsychologia, 41*(9), 1230-1240.

Taylor, S. F., Stern, E. R., & Gehring, W. J. (2007). Neural systems for error monitoring: Recent findings and theoretical perspectives. *Neuroscientist, 13*(2), 160-172. doi: 10.1177/1073858406298184

Thurman, D. J., Alverson, C., Dunn, K. A., Guerrero, J., & Sniezek, J. E. (1999). Traumatic brain injury in the United States: A public health perspective. *Journal of Head Trauma Rehabilitation, 14*(6), 602-615.

Trichard, C., Martinot, J. L., Alagille, M., Masure, M. C., Hardy, P., Ginestet, D., & Feline, A. (1995). Time course of prefrontal lobe dysfunction in severely depressed in-patients: A longitudinal neuropsychological study. *Psychological Medicine, 25*, 79-85.

Tsaousides, T., & Gordon, W. A. (2009). Cognitive rehabilitation following traumatic brain injury: Assessment to treatment. *Mt. Sinai Journal of Medicine, 76*(2), 173-181. doi: 10.1002/msj.20099

Ueno, H., Maruishi, M., Miyatani, M., Muranaka, H., Kondo, K., Ohshita, T., & Matsumoto, M. (2009). Brain activations in errorless and errorful learning in patients with diffuse axonal injury: A functional MRI study. *Brain Injury, 23*(4), 291-298.

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

van Veen, V., & Carter, C. S. (2002b). The timing of action-monitoring processes in the anterior cingulate cortex. *Journal of Cognitive Neuroscience, 14*, 593-602.

Voigt-Radloff, S., Leonhart, R., Rikkert, M. O., Kessels, R. P., & Hull, M. (2011). Study protocol of the multi-site randomised controlled REDALI-DEM trial--the effects of structured relearning methods on daily living task performance of persons with dementia. *BMC Geriatrics, 11*, 44. doi: 10.1186/1471-2318-11-44

Wagner, A. D., Maril, A., Bjork, R. A., & Schacter, D. L. (2001). Prefrontal contributions to executive control: fMRI evidence for functional distinctions within lateral prefrontal cortex. *Neuroimage, 14*(6), 1337-1347.

The Psychological Corporation. (1997). *WAIS-III and WMS-III technical manual*. San Antonio, TX: The Psychological Corporation.

Warmington, M., Hitch, G. J., & Gathercole, S. E. (2013). Improving word learning in children using an errorless technique. *Journal of Experimental Child Psychology, 114*(3), 456-465. doi: 10.1016/j.jecp.2012.10.007

Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology, 54*(6), 1063-1070.

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: 10.1016/j.jad.2008.06.007

Wilcox, R. (2010). *Fundamentals of modern statistical methods: Substantially improving power and accuracy* (2nd ed.). New York: Springer.

Williams, J. M. (1987). The role of cognitive retraining in comprehensive rehabilitation. In J. M. Williams & C. J. Long (Eds.), *The rehabilitation of cognitive disabilities* (pp. 43-55). New York: Plenum Press.

Williams, W. H. (2003). Neuro-rehabilitation and cognitive behaviour therapy for emotional disorders in acquired brain injury. In B. A. Wilson (Ed.), *Neuropsychological rehabilitation* (pp. 115-136). Lisse, The Netherlands: Swets & Zeitlinger Publishers.

Wilson, B. A. (2003). Rehabilitation of memory deficits. In B. A. Wilson (Ed.), *Neuropsychological rehabilitation* (pp. 115-136). Lisse, The Netherlands: Swets & Zeitlinger Publishers.

Wilson, B. A., Baddeley, A., Evans, J., & Shiel, A. (1994). Errorless learning in the rehabilitation of memory impaired people. *Neuropsychological rehabilitation, 4*(3), 307-326.

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*(2), 164-171. doi: 10.1111/j.1467-9280.2006.01680.x

Zaloshnja, E., Miller, T., Langlois, J. A., & Selassie, A. W. (2008). Prevalence of long-term disability from traumatic brain injury in the civilian population of the United States, 2005. *Journal of Head Trauma Rehabilitation, 23*, 394-400.

# Appendix A

*Words used in Errorless learning condition (A & C) and distractors (E).*

| | Stem | List A | List C | Stem | List E |
|---|---|---|---|---|---|
| 1 | (5)AR | ARROW | ARRAY | (5)BE | BEARD |
| 2 | (5)CL | CLOUD | CLOCK | (5)DA | DANCE |
| 3 | (5)DR | DRESS | DREAM | (5)EA | EARTH |
| 4 | (5)HO | HORSE | HOTEL | (5)FA | FAIRY |
| 5 | (5)LE | LEMON | LEVER | (5)KA | KAYAK |
| 6 | (5)PA | PANTS | PATCH | (5)LO | LOLLY |
| 7 | (5)RU | RULER | RUINS | (5)LU | LUNCH |
| 8 | (5)SN | SNAIL | SNIFF | (5)MA | MATCH |
| 9 | (5)TH | THUMB | THIEF | (5)TA | TABLE |
| 10 | (5)WH | WHEEL | WHEAT | (5)VA | VALVE |
| 11 | (6)BA | BASKET | BARREL | (6)DI | DINNER |
| 12 | (6)CH | CHURCH | CHANGE | (6)EM | EMPIRE |
| 13 | (6)HA | HAMMER | HAZARD | (6)GU | GUITAR |
| 14 | (6)JA | JACKET | JAGUAR | (6)JU | JUMPER |
| 15 | (6)LA | LADDER | LAGOON | (6)MU | MUTANT |
| 16 | (6)MO | MONKEY | MODIFY | (6)NA | NATURE |
| 17 | (6)NE | NEEDLE | NEPHEW | (6)OC | OCCUPY |
| 18 | (6)PE | PEANUT | PEPPER | (6)SI | SINGER |
| 19 | (6)TO | TOMATO | TOFFEE | (6)SP | SPIDER |
| 20 | (6)WI | WINDOW | WINTER | (6)YE | YELLOW |

Note. Numbers in parentheses indicate letter count

*Words used in Errorful learning condition (B & D) and distractors (F).*

| | Stem | List B | List D | Stem | List F |
|---|---|---|---|---|---|
| 1 | (5)AP | APPLE | APRON | (5)AL | ALARM |
| 2 | (5)BR | BREAD | BRUSH | (5)CR | CROWN |
| 3 | (5)GL | GLOVE | GLAND | (5)FO | FORGE |
| 4 | (5)HE | HEART | HEAVY | (5)NO | NORTH |
| 5 | (5)KN | KNIFE | KNEES | (5)JE | JELLY |
| 6 | (5)PI | PIANO | PILOT | (5)QU | QUILT |
| 7 | (5)SK | SKIRT | SKILL | (5)SL | SLATE |
| 8 | (5)TI | TIGER | TIMID | (5)ST | STOOL |
| 9 | (5)TR | TRUCK | TRUST | (5)SW | SWING |
| 10 | (5)WA | WATCH | WAGON | (5)YO | YOUTH |
| 11 | (6)AN | ANCHOR | ANTLER | (6)BU | BUTTON |
| 12 | (6)BO | BOTTLE | BOTTOM | (6)EN | ENGINE |
| 13 | (6)CA | CANNON | CANCEL | (6)FR | FREEZE |
| 14 | (6)DO | DONKEY | DOUBLE | (6)IC | ICEBOX |
| 15 | (6)FL | FLOWER | FLAMES | (6)IN | INSECT |
| 16 | (6)OR | ORANGE | ORGANS | (6)KE | KETTLE |
| 17 | (6)PO | POTATO | POLISH | (6)OU | OUTLAW |
| 18 | (6)RA | RABBIT | RATION | (6)PR | PROMPT |
| 19 | (6)SA | SADDLE | SAVAGE | (6)TU | TURTLE |
| 20 | (6)VI | VIOLIN | VIOLET | (6)VE | VENDOR |

Note. Numbers in parentheses indicate letter count