USING DISABILITY RATING SCALE RECOVERY CURVES TO PREDICT PASAT PERFORMANCE AFTER CLOSED HEAD INJURY

A Thesis

Presented to

The Faculty of the Department

of Psychology

University of Houston

In Partial Fulfillment

Of the Requirements for the Degree of

Master of Arts

By

Marika P. Faytell

December, 2014

USING DISABILITY RATING SCALE RECOVERY CURVES TO PREDICT PASAT PERFORMANCE AFTER CLOSED HEAD INJURY

An Abstract of a Thesis

Presented to

The Faculty of the Department

of Psychology

University of Houston

In Partial Fulfillment

Of the Requirements for the Degree of

Master of Arts

By

Marika P. Faytell

December, 2014

ABSTRACT

Objective: Existing predictive models of cognitive outcome following closed head injury have been largely based on a single time-point. Using archival data, the current study sought to improve upon existing models by predicting cognitive outcome at six months post-injury from a model of the rate of recovery of global functioning over four time-points: hospital discharge, one, three and six months post-injury.

Participants and Method: Data from 91 individuals with complicated mild, moderate, and severe closed head injury who had participated in CPHS approved, NIH funded research that involved the collection of global outcome data and neuropsychological testing at six months post injury were used. Disability Rating Scale (DRS) scores from discharge, one, three and six months post-injury were selected along with Paced Auditory Serial Addition Test (PASAT) scores at six months post injury. The PASAT is a task that involves multiple cognitive domains, including processing speed, sustained and divided attention, and working and immediate memory. . Growth curve analysis was used to fit individual growth curves to the DRS scores and then to produce a best-fit recovery curve model. The utility of this model for predicting PASAT scores at six months was determined. Age and severity of injury variables were then added to the model to determine their utility for predicting PASAT scores at six months.

Results: Statistical analyses revealed that only the intercept of the DRS recovery curves significantly predicted PASAT performance at six months post-injury. This finding suggested that only the level of DRS score at one month post-injury, and not the trajectory of recovery, was predictive of later PASAT performance. Higher DRS scores, indicated by larger intercepts, were associated with worse PASAT performance. Age was observed to significantly moderate the relationship between the intercept of the DRS recovery curve and PASAT performance at six months post-injury. Other demographic and severity of injury variables were not observed to significantly moderate the relationship between the intercept of the DRS recovery curves and PASAT performance.

Conclusion: The change of DRS scores over time was fit best by a quadratic growth curve model with random intercept, linear and curvilinear parameters. Only initial DRS scores were significant predictors of later cognitive performance. Age was the only significant moderator of the relationship between initial DRS scores and PASAT performance. Future research could utilize the current study methodology to evaluate the ability of DRS recovery curves to predict performance on less cognitively demanding neuropsychological tests.

ACKNOWLEDGEMENTS

I would like to thank Dr. Hannay for her guidance and support throughout graduate school, and during the Master's Thesis process specifically. Her generous gifts of patience and time are deeply appreciated and cannot be understated. I would also like to thank Dr. Taylor for all his time, dedication and support during the data analysis. He went above and beyond to help me get the models to run correctly. I would also like to thank my thesis committee for their time, their ideas and their invaluable edits. Finally, I would like to thank my family and Derek for their unwavering love, support and encouragement. Having you in my corner made all the difference in the world. This thesis is dedicated to you.

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

Using Disability Rating Scale recovery curves to predict PASAT performance after closed head injury

INTRODUCTION

Traumatic brain injury (TBI) is a serious and growing health concern in the United States and globally. A recent epidemiological study reported that each year, 1.1 million Americans are treated for TBI in emergency departments; 235,000 Americans are hospitalized for a non-fatal TBI; and 50,000 die (Corrigan, Selassie & Orman 2010). Recent estimates suggest that 43 percent of individuals discharged with an acute TBI develop long-term TBI-associated disability. Unsurprisingly, great efforts are being made to predict functional outcome from TBI in research and medical fields (Maas et al. 2007; Marmarou et al. 2007).

However, research efforts are complicated by the umbrella nature of the term "traumatic brain injury," which can include such disparate events as stroke, cardiovascular event, anoxia, car accident or cranial gunshot wound. This use of the term TBI unfortunately includes etiologies that are not produced by the effects of external forces on the brain. Nowadays a more appropriate umbrella term would be acquired brain injury (ABI) leaving the term TBI to be used specifically for "an alteration in brain function, or other evidence of brain pathology, caused by an external force (Menon et al. 2010)."

Closed head injury (CHI) is one type of TBI that receives specific research attention (Gronwall & Wrightson 1981; Pastorek, Hannay & Contant 2004; Satz et al. 1998). CHI is denoted by blunt head trauma that does not result in punctures of the meninges or the brain itself, though skull fractures can occur (Lezak et al. 2012). The frontal and temporal lobes, corpus callosum and other white matter regions like the fornix and upper brainstem are particularly vulnerable to CHI. Damage caused by CHI is typically more diffuse and more generalized than other types of head injury. Diffuse damage affects processing speed, memory and attention, and in cases of more severe injury, problem-solving, high-level concept formation and executive function. The acute stages of recovery from a closed head injury (CHI) can be characterized by rapid changes of a patient's condition, both functionally and cognitively.

Relatively few TBI studies have employed growth curve analyses in predicting outcome. Existing prediction models for cognitive outcome usually do not take into account the course of recovery of global functioning; rather, they predict from one point in recovery to cognitive outcome at another or the same time point. The current study sought to investigate the relationship between the rate of change of global functioning in individuals with complicated mild, moderate and severe CHI and working memory/speed of information processing. This relationship was modeled using growth curve analysis in a retrospective study of previously collected data. Global functioning was measured by the Disability Rating Scale (DRS). Performance on the Paced Auditory Serial Addition Test (PASAT) served as the measure of information processing speed because of its demonstrated sensitivity to TBI-associated cognitive changes, as discussed below.

The literature on the assessment of global outcome with the DRS and other commonly used measures whose efficacy has been compared with that of the DRS was reviewed. The PASAT was reviewed also with particular emphasis on the methodology, reliability, validity, and the neuroanatomical correlates of PASAT performance as measured by fMRI and SPECT.

Finally, the statistical technique of growth curve analysis was discussed as well as its use in neuropsychologically focused research.

The Disability Rating Scale

Description

Much CHI assessment research has focused on developing tools that are sensitive to change. One useful tool is the Disability Rating Scale (DRS), developed by Rappaport and colleagues in 1982. The DRS was designed to be a valid predictor of outcome, and to have high interrater reliability. While the developers comment that the DRS is not difficult to learn or time-consuming to complete, in practice, it appears to be situation-dependent. For instance, in the very acute stages of care, before a patient is sent to a rehabilitation facility, an understanding of all aspects of testing a patient in a coma or emerging from coma may be necessary. It may require the presence of a physician, physician's assistant or a nurse trained in GCS evaluation who can use painful stimuli to elicit a response. Later, when the person returns to the community, the DRS may have to be done over the telephone, so experience in interviewing the individual and family/significant others may be needed. The DRS consists of eight items that fall within the following four categories: arousability, awareness and responsivity; cognitive ability for self-care functions; dependence on others; and psychosocial adaptability for school or work responsibilities required of an employee, student and/or homemaker. Across these categories, the DRS covers a large spectrum of the functional abilities of a patient post-injury. (See the Methods section for further detail.)

Reliability and Validity

Existing research provides support for inter-rater reliability, concurrent validity and predictive validity of the DRS. The initial study evaluated inter-rater reliability of 88 subjects between pairs of three raters (Rappaport et al. 1982). Reported correlations fell between .97 and .98, and were highly significant ($p < 0.01$). Gouvier et al. (1987) also reported highly correlated DRS observations between three raters for 40 participants, with rho values at .98 across the three rater pairs. Further, Gouvier and colleagues (1987) reported high test-retest reliability for the DRS, with a rho correlation of .95.

Regarding concurrent validity, Rappaport et al. (1982) reported that correlational analyses run between DRS scores and independent measures of the participants' central nervous system functioning produced statistically significant correlations between DRS scores and abnormality ratings of visual, auditory and somatosensory brain evoked potentials (r = 0.35-.78). Concurrent validity involving other disability rating scales has also been observed. Gouvier and colleagues (1987) reported a high correlation between initial DRS scores and initial Stover-Zeiger ratings (Stover & Zeiger 1976). Stover-Zeiger (SZ) is an eight-category scale also used to classify recovery in post-coma patients. Initial scores were taken within the first week of admission to an acute rehabilitation center. Similarly, a high correlation between discharge DRS scores and SZ ratings was also observed, with an r of .81.Additionally, Giacino and colleagues (1991) reported a high correlation between the DRS and the Coma Recovery Scale (CRS), with an r of -.93 ($p < 0.01$). The CRS was developed to pick up on subtle changes in neurobehavioral status during an individual's recovery from coma. Finally, Hall and colleagues (1993) reported high significant correlations between the DRS, the Functional Dependence Measure and the Functional Assessment Measure, two other commonly administered disability scales.

Neese and colleagues (2000) investigated bivariate associations between DRS scores and several cognitive domains commonly assessed with neuropsychological testing. Evaluated cognitive domains included academic, intellectual, visuoperceptual, memory, executive functioning and language. Measures included the WAIS-R, TONI-2, WRAT-3 (Reading, Spelling, and Arithmetic subtests), PIAT-R, Controlled Oral Word Association Test, Token Test, Naming task, Sentence Repetition, Facial Recognition, Judgment of Line Orientation, Visual Form Discrimination, Wisconsin Card Sorting Test, California Verbal Learning Test, and Wechsler Memory Scale-Revised (Logical Memory &Visual Reproduction). The sample was comprised of 75 predominately male (73%) individuals with traumatic brain injury with a mean age of 28.84 years (SD = 9.13). The DRS and the neuropsychological assessment were administered during the initial phase of post-acute rehabilitation. Severity of injury was determined by the presence of either emergency room GCS of eight or lower, post-traumatic amnesia for longer than seven days, or length of time greater than one day before the participant is able to follow a command. Eighty-nine percent of participants were classified as having a severe traumatic brain injury.

Neese et al. (2000) reported significant inverse associations between DRS scores and neuropsychological performance, with a range of r values between -0.17 and -0.37 (p <0.05). Better levels of functioning, as demonstrated by lower DRS scores, were associated significantly with better performance across the cognitive domains. Neese et al. (2000) argued that cognitive domains assessed during neuropsychological testing are associated with an individual's ability to navigate everyday activities. Additionally, the reverse argument could be made that an individual's functional abilities are associated with their performance on neuropsychological testing.

Existing research also supports the predictive validity of the DRS. Eliason and Topp (1984) conducted a correlational study to evaluate the ability of the DRS to predict length of hospitalization and status at discharge. The sample was comprised of 128 individuals following cerebrovascular accidents (CVA) or head injuries. Participants were 58 percent male, aged 10-93, with a mean age of 57.35. They were admitted to the study within 72 hours of either acute CVA (69%) or acute traumatic head injury (31%). Eliason and Topp (1984) observed that initial DRS scores were significantly correlated with length of hospitalization, with an r of .50 ($p <$ 0.01). Initial DRS scores were also significantly correlated with discharge status, with an r of .40 ($p <0.01$) and discharge DRS scores, with an r of .66 ($p <0.01$). Higher initial DRS scores were correlated with longer hospitalizations and higher discharge DRS scores.

Gouvier et al. (1987) evaluated the ability of the initial DRS score to predict scores on the Glasgow Outcome Scale and Glasgow Outcome Scale-Extended (GOS-E) at discharge from the acute rehabilitation center in the same sample of 40 patients (as described above). Initial DRS scores were highly correlated with discharge Glasgow Outcome Scale and Glasgow Outcome Scale-Extended scores, with rs of .80 and .85 respectively.

Glasgow Outcome Scale

Description

The Glasgow Outcome Scale (GOS) is widely used in outcome studies, including NIH-NINDS TBI clinical trials. Developed by Jennett and Bond in 1975, the GOS was designed to classify different types of outcomes occurring in patients post-injury (McNett 2007). It met a need for a limited outcome scale that could be used reliably by researchers in several countries, promoting cross-center and cross-cultural data comparison (Jennett et al. 1981). The GOS has five categories that range through good recovery, moderate disability, severe disability, persistent vegetative state, and death. In previous outcome studies, the GOS often has been further dichotomized into favorable outcomes (good recovery and moderate disability) and unfavorable outcomes (severe disability, persistent vegetative state and death) (Choi, Ward & Becker 1983; Teasdale et al. 1998) in order to increase the possibility of finding treatment effects.

Modifications

Although the GOS was originally intended to include mental and social impairments in functional outcome evaluations (Jennett, Snoek, Bond & Brooks 1981), it was observed that GOS raters often made impressionistic ratings (Pettigrew et al. 1998). The GOS structured interview (GOS-S) was designed by Pettigrew and colleagues (1998) to standardize the questions administered to patients to assess GOS outcome category. It included items regarding mental and social impairment in an effort to ensure these areas would not be overlooked and thereby reduce category misassignment (see Appendix B). However, the GOS-S does not address concerns about the insensitivity of the GOS to long-term changes in patient functional ability caused by the broad nature of the GOS outcome categories (Rappaport et al. 1982). To address these concerns, Jennett and colleagues (1981) extended the good recovery, moderate disability and severe disability categories of the GOS in a GOS-Extended version (GOS-E).

Reliability and Validity

The reliability and validity of the GOS and its modifications has been thoroughly established in the literature. A study by Satz and colleagues (1998) demonstrated support for the concurrent validity of the GOS categories 3-5 at six months post-injury in a sample of 100 individuals with moderate to severe traumatic brain injury. Concurrent validity for neuropsychological, psychosocial and functional domains was assessed by separate MANCOVAs. The strongest associations occurred between the GOS category and performance on neuropsychological measures across four domains: motor (F = 12.0-13.2, $p = 0.001$), psychomotor (F = 3.4-8.0, p = 0.02-0.001), memory (F = 2.26 – 6.03, p = 0.050-0.001) and attention (F = 2.7-2.9, p = 0.050-0.035).

Anderson et al. (1993) evaluated the interrater reliability of the GOS when the information was obtained from three different sources: a research psychologist, following neuropsychological assessment and patient interview; the patient's general practitioner; and a research worker, from questionnaires completed by family members. Anderson et al. (1993) reported high interrater reliability between the research psychologist and the research worker, with r of 0.79 (p =0.001). However, the interrater reliability was lower between the research psychologist and the general practitioner, with an r of 0.49 (p = 0.001). General practitioners appeared to give overoptimistic assessments. Additionally, Wilson, Pettigrew and Teasdale (1998) reported high interrater reliability for the structured interviews of the GOS and GOS-E, with weighted kappa values of 0.89 and 0.85 respectively.

Finally, Levin et al. (2001a) compared the validity and sensitivity to change of the GOSS and the GOS-E given with a structured interview in a sample of 43 individuals with mild to moderate traumatic brain injury and 44 individuals who sustained only extracranial injury. They ran separate regression models between each functional outcome measures, affective status and neuropsychological measure and either the GOSS or GOS-E (not dichotomized), to determine an R^2, the square root of mean errors, and the *p* value for each association. The GOS-E was found to have a significantly better fit for the Community Integration Questionnaire (R^2 = 0.35 vs 0.26, $p < 0.01$), trial one of the Paced Auditory Serial Addition Test (R^2 = 0.37 vs 0.19, $p \leq 0.01$), and the Grooved Pegboard time for the right hand (R^2 = 0.21 vs 0.09, p = 0.06 vs 0.08), while the GOSS had a better fit for the Satisfaction score of the Social Support Questionnaire (GOS R^2 = 0.10, $p = 0.05$ vs GOS-E R^2 = 0.12, $p = 0.23$). The associations between other measures and the GOSS and GOS-E were not found to be significant. Taken together, when a linear association is present, the GOS-E was usually a better current predictor of performance on functional outcome and neuropsychological measures and therefore, generally more valid, than the GOSS at three months post-injury. Additionally, while only three individuals with TBI (11 percent) demonstrated a GOSS category change between three and six months post-injury, 10 (36 percent) participants demonstrated a GOS-E category change during the same time period, suggesting that the GOS-E is also more sensitive to change than the GOSS between three months and six months post-injury.

Disability Rating Scale and Glasgow Outcome Scale

Some studies compared the sensitivity of the GOS and DRS with mixed results. In a study of 332 patients with severe TBI, Choi and colleagues (1998) concluded that the DRS is not more sensitive to changes in functional level relative to either the dichotomized or four category GOS (which excludes death). Although they reported a highly significant correlation between the

DRS and GOS scores, Choi and colleagues (1998) observed that some patients who fell into a GOS category of serious disability had a worse DRS score than some patients in the persistent vegetative state GOS category. They considered this finding to reflect a degree of "incoherence" inherent to the DRS, and suggested that the GOS was therefore a better primary outcome measure than the DRS. Given some clinically impossible GOS/DRS combinations in graphic and tabular presentations of the data, these findings merit closer examination before acceptance of the researchers' conclusions.

Hall et al. (1985) compared the sensitivity of the DRS and the GOS over two years post-injury in a sample of 70 individuals with severe head injury. Participants were between 15-60 years of age. Average length of coma was 32 days. Average number of days from injury to admission to the acute head injury rehabilitation unit was 87. Significant correlations between DRS and GOS scores were observed at admission to the unit, with an r of .50 ($p < 0.01$), and at discharge from the unit, with an r of .67 ($p < 0.01$). Hall et al. (1985) reported that the DRS produced a much wider distribution of scores than the GOS, both at admission and at discharge as would be expected given the range of scores for the two scales. The DRS did provide much more specific information about the change in the level of disability for an individual over time; DRS scores revealed that 71 percent of participants changed during the course of hospitalization, while the GOS only reflected change for 33 percent of participants. The DRS was designed to typify the real changes in outcome that take place in severely head injured individuals that cannot be distinguished by the GOS and its extension because of the small number of categories.

Struchen and colleagues (2001) conducted a study of 184 patients with severe TBI who received continuous monitoring of intracranial pressure, mean arterial pressure, jugular venous oxygen saturation and cerebral perfusion pressure. Both GOS and DRS scores were related significantly to longer durations of adverse physiological events across time points. When analyses excluded patients who died, adverse physiological events were related significantly to DRS scores only; the relationship between adverse physiological events and GOS scores became non-significant. These results suggested that the DRS may be more sensitive to changes in a patient's level of functioning, and might be better suited to measuring recovery longitudinally.

As part of an unpublished dissertation, Armstrong (2010) assessed the relationship between patient scores on the DRS and the GOSS, with particular emphasis on checking for implausible score combinations as described above by Choi and colleagues (1998). She summarized the frequency distribution of GOSS score by DRS score at six months post-injury in a table for a sample of 91 individuals with severe CHI. All of the GOSS scores were associated with plausible DRS scores. Additionally, Armstrong and colleagues (2010) observed a strong correlation between scores on the GOSS and the DRS ($r = -.98$, $p < .001$), even when deceased patients were removed from the analysis. Armstrong (2010) also compared models for predicting outcome on the GOS, GOSS, GOS-E and DRS at six months post injury after a severe CHI. The predictors considered for these models included age, gender, ethnicity and years of education as demographic variables, and Best Day 1 GCS motor score, Best Day 1 pupillary response and the first post-injury CT scan classified with the Marshall et al. (1992) criteria as acute care variables. Only age and Best Day 1 GCS motor score consistently made a significant contribution to model prediction. As age increased, the probability of a favorable outcome decreased. As Best Day 1 GCS motor score increased, the probability of a favorable outcome increased. Comparison of models for the GOS-E and DRS revealed that outcome models using four predictor variables (age, education, Best Day 1 GCS motor score and initial CT scan classification) fit the data better when the DRS was included as the primary endpoint. In the DRS model, the predictor variables accounted for more of the variance in outcome at six months post-injury than in the GOS-E model, with age and Best Day 1 GCS motor score uniquely explaining a greater percent of outcome variability. Based on these results, Armstrong (2010) concluded that the DRS was superior to both the GOS-E and the GOS-S as an outcome measure for prognostic conclusions and treatment recommendations.

The Paced Auditory Serial Addition Test (PASAT)

Description

The Paced Auditory Serial Addition Test (PASAT) is a neuropsychological test that is widely used to assess cognitive ability post-CHI. It was first developed by Sampson in 1956, and adapted in 1974 by Gronwall and Sampson as a test of information processing speed and auditory working memory. The PASAT is also considered to be sensitive to other cognitive abilities, including sustained and divided attention and working and immediate memory (Tombaugh, 2006: Lezak et al. 2012).

The PASAT has been adapted in multiple ways over the years. Both auditory and visual versions are administered, and computerized adaptive test (CAT) versions (Tombaugh et al. 2006) have been developed as alternatives to the classic pen and paper tests. The most commonly administered method of the PASAT is the non-computerized auditory version, either the Gronwall, which presents 61 items per trial block (Gronwall & Sampson 1974), or the Levin version, which presents 50 items per trial block (Levin et al. 1987).

The Levin version of the PASAT is presented aurally, with 50 single-digit numbers presented in each of four trials with a precise interstimulus interval (ISI) that decreases across the four trial blocks (Strauss, Sherman & Spreen 2006). The four ISIs are 2.4, 2.0, 1.6 and 1.2 seconds, in order from first trial block to last trial block. Because the participant has to hear the first two successive numbers in order to make the first response, there can only be 49 responses. The participant must remember the first number, add it to the second number and orally give the sum of those numbers. When the participant hears the third number, he/she must forget the first number, then add the second number and the third number and give the sum orally again. This procedure, that is adding the number just heard to the previous number and saying the sum out loud, is followed until the block finishes. For example, if the participant hears 1, 7, 4, then 8, the correct responses would be (nothing), 8 (1+7), 11 (7+4), and 12 (4+8). (For more detailed information on PASAT administration and procedure, see Appendix D and Methods, respectively.) This procedure does not involve a running total, which would be indicative of the participant not following the test instructions.

Modality-specific factors have been observed to affect PASAT performance. Hiscock, Caroselli and Kimball (1998) reported that individual performance on the PASAT is affected by both input and output modalities. Individuals tended to perform better on a visual analogue of the PASAT, where digits were presented visually in Arabic numerals at the same ISIs as the PASAT, and participants were still expected to give verbal responses. Individuals also tended to perform better when asked to give written responses to the PASAT instead of oral ones, though only during trials with standard PASAT ISIs. These results indicate that PASAT performance is not only a measure of general attentional capacity or processing speed. For example, poor performance on the PASAT could reflect the effects of auditory-verbal interference instead of impairment in processing speed. However, a standard auditory PASAT procedure was used in the current study.

Cognitive Domains Measured by the PASAT – Factor Analytic Studies

The PASAT is thought to measure several cognitive domains, particularly sustained and divided attention and information processing speed. Gronwall and Wrightson (1981) conducted two varimax rotated factor analyses. Both analyses included performance on the Quick-test, Wechsler Memory Scale subtests (Information + Orientation, Mental Control, Logical Memory, Digit Span, Associate Learning) and the PASAT. All patients had sustained ‘simple’ head injuries within a week to a month of injury. For the first analysis (n=71), PASAT performance loaded most highly onto a factor with the Mental Control, possibly defining an isolated attention and concentration factor. The Information and Orientation and the Quick-test appeared to define a general knowledge and verbal competence factor, which was suggested to reflect the level of premorbid ability. Finally, the Paired Associates and Visual Recall loaded onto a third factor that appeared to define an isolated learning and memory factor. The second analysis included only patients with a PTA duration of at least an hour (n=51). PTA loadings on all factors were relatively low; otherwise the factor results were similar.

Similarly, O’Donnell and colleagues (1994) conducted a rotated varimax factor analysis of age-corrected standard scores on the PASAT (total correct responses), the Category Test (total errors), the Wisconsin Card Sorting Test (perseverative response score), the Visual Search and Attention Test (total correct cancellations), and the Trail Making Test, Part B (time) in a sample of 117 community-dwelling individuals who were referred for rehabilitation services for varied neurological, genetic and psychiatric diagnoses (n = 22 with minimal diagnosis of concussion). They also found that the PASAT loaded most strongly onto an isolated factor with other attention and information processing tests, including the Visual Search and Attention Test and the Trail Making Test, Part B. The Wisconsin Card Sorting Test and the Category Test loaded onto a separate factor, possibly a conceptual factor.

Finally, Larrabee and Curtiss (1995) conducted a factor analysis on information processing, attention, verbal and visual memory scores of 112 neuropsychological outpatients with a variety of neurological and psychiatric diagnoses, including CHI (n = 35), somatoform disorder, seizure disorder, depression and alcohol abuse. CHI severity was not described, but individuals with aphasia, neglect or who demonstrated evidence of questionable motivation (e.g. worse-than-chance performance on CRM or CVMT) were excluded from the study. Participants were administered the Expanded Paired Associates Test, the Verbal Selective Reminding Test, the Continuous Recognition Memory Test, the Continuous Visual Memory Test, the PASAT, the WMS Mental Control and Visual Reproduction subtests, the WAIS-R Digit Span, Block Design and Object Assembly subtests, the Trail Making Test and Serial Digit Learning. Larrabee and Curtiss (1995) reported that performance on the PASAT loaded onto an attention/information processing factor; other tests that loaded onto this factor included the WMS Mental Control, WAIS-R Digit Span and Serial Digit Learning. The Expanded Paired Associates Test, the Verbal Selective Reminding Test, the Continuous Visual Memory Test, the Continuous Recognition Memory Test, Serial Digit Learning and WMS Visual Reproduction loaded onto a general visual and verbal memory factor. WAIS-R Block Design, Object Assembly, Trail Making Test Part B, and WMS Visual Reproduction loaded onto a visuospatial intelligence/ability factor. Finally, the

Information and Vocabulary Subtests of the WAIS-R loaded onto a general intelligence factor. Together, these factor analyses support the conclusion that the PASAT is more similar to other tests of attention and information processing than it is to tests of memory or verbal knowledge.

Validity

Sherman, Strauss and Spellacy (1997) evaluated the construct and criterion-related validity of the PASAT in a sample of 441 adults referred for neuropsychological evaluation of possible closed-head injury. The Wilson (1984) version of the PASAT was administered. This version was presented in an unavailable unpublished manuscript, as described by Sherman, Strauss and Spellacy (1997). It consists of two trial blocks, with 2 second and 1.6 second ISIs respectively, which are equivalent to two of the trial blocks of the Gronwall and Levin versions of the PASAT. As a test of convergent validity, Sherman et al. (1997) hypothesized that the PASAT would correlate moderately or highly with other tests of attention, including the WAIS-R Arithmetic, Digit Span and Digit Symbol subtests, Sentence Repetition, the Brown-Peterson Consonant Trigrams, the Corsi Block Test, the D2 cancellation test, the interference trial of the Stroop, and the Trail Making Test. As a test of divergent validity, they hypothesized that the PASAT would have only small correlations with tests of other modalities, like the WAIS-R Full Scale IQ, GATB General Learning Ability and Numerical Aptitude, Raven's Progressive Matrices, the Wonderlic Personnel Test, the WRAT-R Arithmetic subtest. They reported that the convergent evidence for construct validity of the PASAT as a test of attention was stronger than divergent evidence. PASAT performance correlated with several measures of attention; however, a substantial amount of the variance in PASAT scores was accounted for by tests measuring mathematical knowledge. PASAT performance was also found to correlate moderately with other tests measuring conceptually unrelated abilities, including verbal ability, verbal memory, academic achievement, and complex motor skills. These results suggest that PASAT scores are related to several cognitive abilities additional to attention and processing speed.

Other studies have evaluated the predictive validity of the PASAT. The PASAT has predicted later post-concussive syndrome (PCS), particularly when part of a larger battery. A study by King (1996) found that a combination of eight neuropsychological, emotional and traditional measures of head injury severity (including the PASAT) administered 7-10 days post injury were predictive of persistent post-concussive syndrome (PCS) severity three months later. The sample was comprised of 50 head-injured adults of varying severity, aged 17-65 with a mean of 33 years. A combination of scores from six of the measures gave a multiple correlation coefficient of R = 0.86, accounting for 74 percent of the variance in scores on a PCS rating scale. The scores included the 2.4, 1.6 and 1.2 ISI trial blocks from the PASAT, the speeded word reading subtask from the Stroop, the Hospital Anxiety and Depression Scale, the length of PTA in hours, the Short Orientation and Memory Concentration Test, and the Information Processing subtest of the Adult Memory and Information Processing Battery.

Additionally, the ecological validity of the PASAT and other neuropsychological tests was evaluated in a sample of 31 cognitively and functionally impaired Caucasian individuals at a mean age of 46.7 (SD = 7.6) with definite or probable multiple sclerosis (Higginson, Arnett & Voss 2000). The version of the PASAT used for this study was comprised of two trials of 60 single-digit numbers. ISIs for the two trials were three and two seconds respectively. The dependent variable for each trial was the total number of correct responses. Ecological validity was measured using the Environmental Status Scale, which is a scale of broad functional ability.

Participants and their significant others (when available) were interviewed to assess the participant's difficulty completing everyday tasks. The scale had seven items: employment status, requirements for personal assistance, requirements for community assistance, financial/economic status, social activity, modifications to residence, and ability to use transportation. Each task was then assigned a value on a six-point (0-5) Likert scale, with higher values indicating more experienced difficulty. PASAT performance across both trials was found to correlate significantly with the Environmental Status Scale scores at a correlation coefficient of $R = -.30$ ($p<0.05$). However, PASAT performance was not found to be a significant predictor of Environmental Status Scale Scores in a stepwise regression analysis comparing tests of attention.

Finally, Benedict and colleagues (2006) conducted a study of a brief assessment of cognitive function in multiple sclerosis (MACFIMS) battery, comparing 291 individuals with a diagnosis of definite MS to 56 healthy controls. The PASAT was included in this battery, but also modified to two blocks of 60 trials, with ISIs of three and two seconds respectively. The dependent variable was the number of correct responses from the two trials. Principal component analysis demonstrated that the number of correct responses on the three-second block of trials on the PASAT was predictive of current disabled/employment status (odds ratio 3.57, $p = 0.03$), according to the statistical model employing a more conservative definition of disabled/employment status.

Overall research findings for the PASAT confirm its role as another test of attention, working memory, and mathematical knowledge, but not as a measure of other cognitive domains. The PASAT also appears to make a small but significant contribution to predicting current and future behavior in naturalistic settings across disease states. Further research into the predictive validity of the PASAT might better elucidate the relationship between the PASAT and global functioning.

The PASAT and Traumatic Brain Injury

TBI is known to affect multiple cognitive domains, including memory (particularly short-term memory), attention, language, processing speed, concept formation, complex reasoning and executive functioning (Lezak et al. 2012). As previously stated, the PASAT is sensitive to several of these cognitive domains and has been used for assessing cognitive impairments common to individuals with TBI. Ponsford and Kinsella (1992) used the PASAT, Stroop, Symbol Digit Modalities Test, Cancellation, and simple and choice reaction-time tests to measure attentional deficits in a sample of 47 individuals with severe closed-head injury and 30 controls. Severity of injury was determined by at least seven days of PTA. Admission GCS scores were documented for 38 of 47 patients, and fell within a range of 3-9. All individuals with head injury were less than 12 months post-injury. Ponsford and Kinsella (1992) reported that the only significant differences in error scores between head-injured and control groups was observed during PASAT performance; head-injured individuals performed significantly worse than controls across all PASAT trials.

Similarly, in a study comparing 35 individuals with severe non-penetrating TBIs with 35 age- and education-matched controls, Bate, Mathias and Crawford (2001) reported that PASAT performance was significantly lower for the TBI group at the shortest ISI (1.2 seconds) and marginally significantly lower at the second shortest ISI (1.6 seconds).

In a study of outcome three to five years after traumatic brain injury, Dikmen and colleagues (2003) administered the Levin version of the PASAT and the CVLT to a sample of 210 individuals with mild to severe traumatic brain injury, as measured by the Head index of the Abbreviated Injury Scale (AIS-Head). Severity rating was based on the length of loss of consciousness, the presence of non-transient neurological deficits, and the presence, location, size and multiplicity of anatomical lesions. Participants were predominately male (82%) and an average age of 36. Time since injury was an average of 3.49 years (SD = .60). They reported a systematic relationship between modified AIS-Head score and performance on the PASAT; participants with more severe AIS-Head ratings performed significantly worse on the PASAT.

Finally, Vanderploeg and colleagues (2005) investigated long-term neuropsychological outcome following minor or mild uncomplicated traumatic brain injury in a retrospective sample of 4384 Vietnam veterans. Within the sample, 3214 were healthy controls, 539 had been in a motor vehicle accident but had not sustained a head injury, and 254 had a head injury with altered consciousness. The remaining 377, who reported a head injury but did not experience altered consciousness, were excluded from the analyses. While they did not observe significant group differences for number of correct responses on the PASAT, Vanderploeg et al. (2005) reported that individuals with mild traumatic brain injury had significantly lower rates on trial block three of the PASAT than individuals in the two control groups. The completion rate for trial block four followed the same trend as for trial block three, but there was no statistically significant difference between groups. The results suggest that even though they may not perform differently from healthy controls, individuals with mild traumatic brain injury may be less likely to complete all four trial blocks of the PASAT. Common clinical and research practice for neuropsychological assessment is to strongly encourage participants to attempt all measures. Vanderploeg et al. (2005) stated that they allowed participants who were particularly upset or too frustrated to discontinue the PASAT, due to fear that the participant would withdraw further participation. This may be an atypical procedure, given that many neuropsychologists prefer to leave PASAT administration to the end of their battery so as not introduce difficulties that may affect the outcome of following tests.

The PASAT and Neuroimaging

Previous functional magnetic resonance imaging (fMRI) studies of PASAT performance in healthy controls have supported a consistent general activation pattern involving both frontal and parietal areas, with greater activation observed in the left hemisphere (Audoin et al. 2005; Forn et al. 2008; Tudos et al. 2014). This pattern is consonant with known patterns of activation in the attention, working memory and calculation literatures (Lezak et al. 2012; Heilman & Valenstein 2011). Attentional tasks are known to correlate with activation in the prefrontal cortex, posterior parietal cortex, the white matter tracts, and the cerebellum (Lezak et al. 2012). Tasks involving working memory correlate with activation in the left inferior parietal lobule, the medial temporal lobes, the dorsolateral prefrontal cortex, and the cerebellum (Lezak et al. 2012). Finally, the left hemisphere is thought to be the primary mediator of the numerical symbol system, and is activated during linear arithmetic problems (Lezak et al. 2012). Further, anarithmetria (or primary acalculia), an acquired impairment associated with difficulty performing simple calculations, such as addition and subtraction, is associated with left hemisphere lesions (Heilman & Valenstein 2011). The calculation literature also indicates some left parietal involvement, as acalculia is observed to follow left parietal damage in a number of case studies.

Differences between study results were observed with regard to specific regions within the frontal and parietal lobes, as well as within other cortical and subcortical regions. Notably, not all of the studies described cerebellar activation. However, the cerebellum is highly relevant for PASAT neuroimaging studies, as it is known to be involved in a number of cognitive functions, including attention and working memory (Lezak et al. 2012). Neural pathways connect the frontal, parietal and superior temporal lobes to the cerebellum through the pons; the cerebellum sends corresponding ascending pathways through the thalamus back to those cortical areas.

Audoin et al. (2005) sought to determine regions of activation during PASAT performance in a sample of 10 young, right-handed, primary French-speaking healthy controls. Age and education demographic data are not quite clear, with means and SDs suggesting that the participants could be as young as children and as old as middle aged. Participants were exposed to one PASAT trial consisting of 61 single-digit numbers presented at a three second ISI, and one control trial comprised of the same series of numbers, during which the participant was asked to repeat the numbers following each presentation.

Audoin et al. (2005) observed activation specific to PASAT performance in the left dorsolateral prefrontal cortex, which is associated with working memory, and the left frontopolar cortex, which is associated with attention. Activation was also observed in the left parietal lobe, which is consistent with known working memory, attention and calculation activation patterns. Activation in the left superior temporal gyrus, the left temporal pole and the cingulate gyrus may have been associated with working memory. Activation observed in the supplementary motor cortex, the lateral premotor cortex, and the visual associative areas may have reflected the mechanics of the task: motor movements associated with vocalization, visualizing the numbers, etc. The mean scores of successful responses, false responses (commissions) and no responses (omissions) of the participants in the scanner were comparable to the scores obtained by a larger cohort at the same institution under conventional conditions.

Forn and colleagues (2008) evaluated potential differences in activation during the PASAT when responses were given covertly (silently) versus overtly (verbally). A sample of 14 young (mean age: 21.9; SD: 1.6) right-handed, primarily Spanish speaking undergraduates was exposed to two six-minute versions of the PASAT. Each version was comprised of six one-minute blocks. Three blocks were control blocks, where participants were asked to repeat each number they heard. During the three test blocks, participants were asked to sum the two most recent numbers and either think about the answer (the covert version) or give it verbally (overt version) as in the versions of the PASAT described previously. Across all blocks, numbers were presented at a three second ISI. The number of correct responses was collected during the overt versions. All participants performed within the normal range of the PASAT, with more than 75 percent correct responses.

Forn et al. (2008) reported that activation patterns for the two versions were largely similar. During both versions of the task, activation was observed in the prefrontal superior gyrus, the middle frontal gyrus, and the inferior frontal gyrus, which are associated with working memory and attention. Activation was also observed in the superior parietal region and the inferior parietal region; the parietal lobe is associated with attention, working memory and calculation (Lezak et al. 2012; Heilman & Valenstein 2011). Additionally, greater activation was observed in the left hemisphere across task versions, which is consistent with the calculation literature (Heilman & Valenstein 2011).

During the overt version, which is more similar to the version of the PASAT commonly used in neuropsychological assessment, significantly greater activation was observed in the left superior and inferior frontal gyrus, the bilateral occipital cortex, the caudate nucleus, the cerebellum and substantia nigra (Forn et al. 2008). Activation in the caudate nucleus and substantia nigra might have been associated with motor planning involved in producing a verbal response, which is an aspect of any spoken response .Frontal and cerebellar activation are consistent with the literature on attentional and working memory (Lezak et al. 2014) , and occipital activation may reflect number visualization; however, the explanation for why these areas are activated more during the overt task is not immediately apparent, nor is it provided by the authors.

Finally, Tudos and colleagues (2014) compared activation patterns of 20 healthy controls during the PASAT and the Paced Verbal Serial Addition Test (PVSAT). The PVSAT is similar to the PASAT, but numbers are presented visually instead of aurally. A sample of 20 young (mean age: 23.0; SD: 2.7) right-handed university students or recent graduates was administered four six-minute runs. The PASAT was given during two of the runs. Participants' eyes were closed during the PASAT administration. The PVSAT, adapted for the MRI setting, was given during the other two runs. Each run was comprised of six 30-second blocks, during which the participant was asked to raise a thumb when the two most recent numbers summed to 10. These blocks were alternated with six 30-second control blocks, during which the participant was asked to raise a thumb when 10 was presented. All numbers were presented at a three second ISI. The number of correct responses to the target was calculated for the PASAT and the PVSAT.

Tudos et al. (2014) observed a common pattern of activation between the two tasks, which included activation in the bilateral supplementary motor area, the insular cortex and the right caudate, which are consistent with the motor response (thumb-raising). Activation observed in the left inferior frontal gyrus, the bilateral inferior frontal junction, the right middle frontal gyrus, the bilateral intraparietal sulcus, the vermis, and the bilateral cerebellum is consistent with the literature on working memory and attention. They also reported modality-dependent areas of activation. Greater activation during the PASAT was observed in the right frontal eye field, the right lingual and fusiform gyrus, the left lingual gyrus, the right intracalcarine cortex, and the left occipital pole. Greater activation during the PVSAT was observed in the bilateral LO1 lateral occipital complex, the left LO2 lateral occipital complex, and the fusiform gyrus. The authors hypothesized that activation in the right frontal eye field resulted from symmetrical activation during the PASAT, while activation was lateralized during the PVSAT, with greater left-sided activation. They attributed the greater activation in the striate and extrastriate cortices listed above during PASAT as due to a combination of activation during the PASAT and deactivation during the PVSAT. These areas may have been activated during the PASAT due to participant use of visual imagery. The same areas were deactivated during the PVSAT because the task made lower relative demands on primary visual areas, and higher relative demands on higher visual processing areas, such as the lateral occipital cortex.

Previous fMRI studies of individuals with mild to severe TBI demonstrate differential patterns of activation in individuals with brain injury during the PASAT. Christodoulou and colleagues (2001) measured brain activation patterns of nine individuals with moderate and severe TBI and seven healthy controls during a modified version of the PASAT. TBI severity was based on an unspecified GCS score for six patients; severity for the other three patients was determined by the presence of anatomical findings on neuroimaging, positive focal neurological signs, or loss of consciousness longer than 30 minutes. The mean time since injury was 51.33 months, with a standard deviation of 41.07 months, suggesting a large range of time since injury across the nine participants with TBI. Participants were scanned during a 32 second baseline period during which no cognitive or motor activities were administered. This was followed by four sets of 32-second trial blocks. The PASAT was given during the first and third 32-second blocks. Numbers were presented at a two second ISI. Participants were instructed to silently add the two most recent numbers, and to lift their right index finger when they reached a sum of 10. This response was designed to limit artifacts from head movement. Responses were collected by an observer. The second and fourth blocks were the control trials; participants were asked to imagine brushing their teeth. This task was chosen because it would require some attention without working memory.

Christodoulou et al. (2001) reported that individuals with TBI were able to perform the task but made significantly more errors of omission than the healthy controls. Brain activation patterns were similar for the two groups in that activity was observed in similar regions of the frontal, parietal and temporal lobes. Additionally, this pattern was consistent with previous studies of working memory in healthy controls (Audoin et al. 2005; Forn et al. 2008; Tudos et al. 2014). In contrast, cerebral activation in the individuals with TBI was more regionally dispersed and more lateralized to the right hemisphere, with lateralization differences most evident in the frontal lobes.

However, aspects of the study design limit the applicability of the results. Ongoing plasticity of neural circuits indicate that the brain does not remain stable in the months and years following a traumatic brain injury. Consequently, the large range of time since injury across participants means that activation is being sampled and compared at very different stages of the recovery process. Additionally, the control task does not closely resemble the experimental task. Usually, control tasks try to mimic the task as closely as possible, without including experimental element: in this case, the mental manipulation of numbers. Examples of control tasks for the PASAT include responding when a specific number is heard (Tudos et al. 2014), or repeating each number presented (Audoin et al. 2005; Forn et al. 2008). Imagining brushing teeth does not control for the motor response, the auditory response to aural input, or thinking about numbers in general. The task further introduces a number of different domains that may interfere with the domains of interest, including visual imagery, somatosensory imagery, and motor planning. Although the results were consistent with previous research, these limitations indicate that the study results should be interpreted with caution.

Sensitivity of PASAT performance to subtle cognitive changes post-mild TBI has been supported by neuroimaging. Hattori et al. (2009) sought to explore mechanisms for cognitive fatigue commonly associated with mild TBI. In a single-photon emission computed tomography (SPECT) study measuring regional cerebral blood flow, they found that individuals with mild TBI demonstrated a differential pattern of activation from a control group when attempting the PASAT. Fifteen individuals with mild TBI and 15 healthy controls underwent SPECT at rest and during the PASAT on a separate day. Severity of TBI was determined by the definition put forth by the mild TBI brain injury committee of the Head Injury Interdisciplinary Special Interest Group of the American Congress of Rehabilitation Medicine (ACRM) (See Appendix B). The TBI sample was primarily female (n =12) aged 27-60 with a mean of 45 years. Image analysis revealed that healthy controls showed bilateral activation in the superior temporal cortex, the precentral gyrus (Brodmann area [BA] 6) and the cerebellum, as well as activation in the left precentral gyrus (BA 9). These results are consistent with attention, working memory and calculation. Conversely, individuals with mild TBI showed larger areas of supratentorial activation (BAs 9, 10, 13 & 46) but smaller areas of cerebellar activation, suggesting frontocerebellar dissociation.

Growth Curve Analysis

Growth curve analyses and their utility for TBI research need to be discussed in order to understand the hypotheses, design, analysis and interpretation of the data in this study. Previous outcome studies have largely focused on the level of neuropsychological and functional recovery reached after six months (Pastorek, Hannay & Contant 2004; Satz et al. 1998) or one year (Levin et al. 1990). Fewer studies have sought to model the rate of recovery post-injury (Ewing-Cobbs et al. 2004; Levin et al. 2001b). Growth curve analysis (GCA) allows researchers to study the rate of change of a variable over time using multilevel models of potential growth patterns (Field 2011). Growth curves have three components: the intercept, the linear component (slope) and the curvilinear component. These components are expressed with the following equation for an individual subject (Francis, Schatschneider & Carlson 2000):

$$Y_t = \pi_0 + \pi_1 a_t + \pi_2 a^2{}_t + \pi_3 a^3{}_t + \pi_4 a^4{}_t + \ldots + \pi_{k-1} a^{k-1}{}_t + E$$

where k is the number of time points, and π represents the individual's growth parameters. Parameter values are subject-specific. The growth parameters are demarcated by the numerical subscripts 0 to k - 1, and represent the order of the polynomial term. The term a_t is a marker of time. The subscript t represents a given point in time from 1 to k. The term E represents random error in Y at time t, and is assumed that E is normally distributed and uncorrelated across subjects.

The intercept is a constant and models outcome at the time point at which it is centered. Centering the intercept helps to avoid multicollinearity. It is expressed with the subscript 0 as π_0. The linear component models a constant rate of change, and is expressed with the subscript 1 as $\pi_1 a_t$. Finally, the curvilinear component represents changes in the rate of change (like acceleration or deceleration), and at the largest can be represented by $\pi_{k-1} a^{k-1}{}_t$, or a polynomial of order k – 1 with k time points, though usually the polynomial is a much lower order. Consequently, individual growth patterns can be linear ($Y_t = \pi_0 + \pi_1 a_t + E$), quadratic ($Y_t = \pi_0 + \pi_1 a_t + \pi_2 a^2{}_t + E$), cubic ($Y_t = \pi_0 + \pi_1 a_t + \pi_2 a^2{}_t + \pi_3 a^3{}_t + E$), or exponential ($Y_t = \pi_0 + \pi_1 a_t + \pi_2 a^2{}_t + \ldots + \pi_{k-1} a^{k-1}{}_t + E$). These individual growth curves are fit to longitudinal data to determine which trend best models the change in the outcome variable across subjects over time.

Additional variables can be added to growth curve models to evaluate their relationships to the change of the independent variable over time (Francis, Schatschneider & Carlson 2000). Variables that correlate with change also relate systematically with the variability of the individual growth curve parameters. These variables can include demographic variables, such as age, level of educational attainment or race/ethnicity. Studies evaluating correlates of change must include a second model where each individual parameter, or π, is a dependent variable, modeled by the resultant equation for an individual:

$$\pi_{\mathrm{k}} = \beta_{k0} + \pi_{k1}X_{k1} + \beta_{k2}X_{k2} + \cdots \beta_{k(p-1)}X_{k(p-1)} + R_k$$

where there are *p* – 1 measured moderator variables. β_k reflects the effect of the *p*th moderator variable on the *k*th growth parameter. R_k is random error. It is unnecessary to assume that the moderator variables each affect all the growth parameters.

Growth curve models are hierarchical in nature, due to the nesting of multiple time points within the individual participants. As a consequence, hierarchical linear modeling has been proposed as an appropriate methodology for estimating the parameters of individual growth curves (π) and analyzing the variability in these estimates (Francis, Schatschneider & Carlson 2000). However, navigating the balance between the lack of independence among the observations at the lower levels of the hierarchy and the low power for testing hypotheses on independent observations at the top of the hierarchy can be tricky. This balance has been addressed by using maximum-likelihood and general least-squares estimates to permit the development of multilevel models and estimation of individual parameters across all levels of the model. This approach is comprised of two simultaneous stages. The first stage is a within-subject multiple regression analysis conducted to estimate the individuals' intercept and slope parameters. The second stage is an examination of the ability of individual differences between participants to predict differences in the growth parameters, conducted as a between-subject analysis with the estimates of the intercept and slope parameters as the dependent measures.

Growth curve analysis has been applied to measures of academic achievement and cognitive ability in children to determine the rate of recovery of cognitive and learning abilities after pediatric TBI. To model longitudinal academic achievement after pediatric TBI, Ewing-Cobbs and colleagues (2004) administered a short neuropsychological battery to children aged five to 15 following mild, moderate or severe TBI at one, two, three, four. and five or more years post-injury. Participants received three to seven evaluations. The battery was comprised of the Reading Recognition, Spelling and Arithmetic subtests from the Wide Range Achievement Test (WRAT) and the Reading Comprehension subtest from the Peabody Individual Achievement Test (PIAT).

Individual growth curve analyses were used to characterize change in unadjusted academic achievement scores over time for children with mild-moderate (N= 34) and severe (N= 43) brain injury. Participants were further separated into three different age groups at injury for analysis: five to seven years old, eight to 11 years old and 12 to 15 years old (sample sizes not provided). Scores were expressed as functions of time since injury. A three parameter polynomial function of time was used to approximate the models, with intercept, linear component and curvilinear component as the parameters. To minimize multicollinearity and because it is a reasonable time period for group comparison, the time was centered at one year post-injury. Consequently, the intercept modeled outcome at one year post-injury. The linear component modeled the rate of growth in the outcome variable. The curvilinear component modeled the change of the linear component over time.

For WRAT Arithmetic scores, a model with a random intercept, a random linear component and a fixed curvilinear component best fit the data. A significant covariation was reported between the intercept and the linear component, and was suggestive of faster rates of score increases for children with lower scores at one year post-injury than for children with higher scores. The addition of age at injury and duration of coma to the model indicated that older children had lower initial scores, but their scores accelerated more over time than the scores of younger children. Growth curves grouped by age at injury and TBI severity for WRAT Arithmetic scores can be found in Figure 1 (Appendix A). Significant variance in intercepts, linear components and curvilinear components was indicated for WRAT Spelling scores. The linear and curvilinear components were found to be significantly related, indicating that children whose scores increased at a faster rate relative to the norm (i.e. larger linear component) demonstrated rates of increase that slowed more over time (i.e. smaller curvilinear component). Addition of injury severity to the model revealed that children with severe TBI had lower initial spelling scores, which increased over time at a decelerated rate, as reflected by decelerating recovery curves. Spelling scores of children with mild or moderate TBI fit a linear curve over time, demonstrating continuing improvement compared to the norm group. Age at injury and the interaction of age at injury were not found to be significantly related to any of the parameters.

For WRAT Reading Recognition scores, the intercept and linear component had significant variance when the curvilinear component was fixed. Addition of age at injury and duration of coma to the model revealed that lower word-decoding scores were associated with children with severe TBI. Older children demonstrated greater increases in reading scores than younger children. Rate of change was found to decelerate over time for all groups, though across groups scores generally increased over time.

Finally, for the PIAT Reading Comprehension, the intercept and linear component had significant variance when the curvilinear component was fixed. The covariance between the intercept and linear component was nonsignificant. Addition of injury severity and age at injury to the model revealed that children with severe TBI scored significantly lower than children with mild or moderate TBI, and older participants tended to have lower scores than younger participants. Injury severity, age at injury and their interaction were not predictive of the linear or curvilinear components.

Levin and colleagues (2001b) used growth curve analysis to evaluate the effects of age at injury and severity of injury (mild CHI N = 44, severe CHI N = 78) on recovery of word fluency in a sample of 122 children ages five to 15 with mild or severe CHI. The COWA, PPVT-R and the CVLT-C were administered at three, six, 12, 21, 36, 48, and 60 months post injury. Each participant was assessed at three or more time points.

The word fluency data were fit best by a model with a random intercept and a random linear component (Levin et al. 2001b). The triple interaction between age at injury, the interval duration between evaluations, and severity of injury was found to be significant. This result indicated that recovery of word finding was slower after severe CHI in younger children, compared to severe CHI in older children or mild CHI in younger children. The interaction between interval and age at injury was also significant, and revealed that the effect of the interval duration was stronger for younger children. The main effects of CHI severity, interval duration and age at injury were also found to be significant.

Growth curve analysis of the raw data from the PPVT-R indicated a significant effect of interval duration and age at injury (Levin et al. 2001b). An interval by interval effect and a group effect were also found to be significant. Finally, there was a significant interaction between interval duration and age at injury, which suggested that receptive vocabulary increased more rapidly after injury in young children, compared with older children and adolescents. Parallel improvement of receptive vocabulary over time was observed for the mild and severe CHI groups.

Growth curve analysis of word list recall scores as measured by the CVLT-C also demonstrated greater improvement in verbal recall over time since injury in younger children compared to older children (Levin et al. 2001b). A decrease over time between word list recall scores for mild and severe CHI children was also evident.

McCauley and colleagues (2001) applied growth curve analysis to DRS scores taken at discharge from the acute care hospital, one, three and six months post-injury to model rate of recovery from CHI. They hypothesized that an individual's recovery curve would be predictive of the level of neurobehavioral and affective disturbance as measured by the HI-FI Problem Checklist (Kay, Cavallo, Ezrachi and Vavagiakis 1995; Veramonti, 2004) at six months post-injury, as determined from the perspective of their significant other (SO).The intercept was centered at the one month DRS evaluation post-injury to avoid multicollinearity. The model that best fit the data included a random intercept, a random linear component and a fixed curvilinear component. The intercept and linear component were found to have significant random variation, and the two terms were inversely related, indicating that the higher the DRS at one month post injury, the larger the negative linear component. Tests of fixed effects on the ability of the DRS recovery curves to predict the affective/neurobehavioral symptom severity at six months post-injury demonstrated that the intercept was not related to the outcome. Similarly, the intercept was not found to be significantly associated with SO-perceived severity and burden of cognitive deficits. However, the linear and curvilinear components were found to be significantly related to SO-perceived severity of neurobehavioral impairments and severity and burden of cognitive deficits. These results suggest that the initial DRS score at one month post injury is not as important as the rate of decline in DRS score for predicting the SO's perception of the patient's affective/neurobehavioral disturbance or the severity and burden of cognitive deficits.

The Current Study

The current study sought to investigate the relationship between change in global functional outcome on the DRS over the first six months after CHI and aspects of divided and sustained attention, information processing speed, and working memory as measured by the PASAT. DRS scores at discharge, one, three, and six months post injury were transformed into individual growth curves, components of which were used to predict PASAT performance at six months post injury. Potential covariates such as severity of injury variables (Best Day 1 GCS score and Marshall CT classification) and demographics (age, education, ethnicity) and were included in the models to determine their contribution to the statistical models.

Hypotheses

1. The trajectory of recovery, modeled by the linear and curvilinear components of the DRS recovery curves, would be more predictive of cognitive performance on the PASAT at six months post-injury than the intercept alone.

This hypothesis is consistent with the findings of McCauley et al. (2001). Although the intercept was not significantly associated with any of the stated outcomes, the linear and curvilinear components of the DRS recovery curves were significantly associated with the SO-perceived severity of cognitive deficits, cognitive burden, and affective/neurobehavioral symptoms. These results suggested that the initial DRS score at one month post injury was not as important as the declining linear and curvilinear rates (i.e. decelerating negative rate of change) in DRS score for predicting the SO's perception of the patient's cognitive, affective, or neurobehavioral outcomes.

2. Steeper negative DRS recovery curves, as modeled by larger negative linear and curvilinear components, would be associated with better PASAT performance at six months post-injury.

This hypothesis is also consistent with the findings by McCauley et al. (2001), which demonstrate that DRS recovery curves with large negative linear and curvilinear components were found to be associated with lower SO-perceived severity of affective/neurobehavioral symptoms, cognitive deficits and cognitive burden at six months post-injury.

3. Age was predicted to significantly moderate the association between DRS recovery curves and performance on the PASAT at six months post-injury. Specifically, the older the participants, the flatter DRS recovery curves (smaller linear and curvilinear components), were predicted to be, and the greater the intercept (the higher the DRS score) and the lower the PASAT score were expected to be at six months post-injury.

This hypothesis is well supported by the existing TBI recovery literature, where age is known to be a significant covariate in TBI recovery models. Older adults show less improvement at one year post-injury, have more complications, and are less likely to survive a severe injury than younger adults (Lezak et al. 2012). The significance of age is reflected by the Levin et al. (2001b) growth curve study outlined above, which demonstrated that the rates of recovery of word finding, receptive vocabulary, and verbal recall are affected by the child's age at injury. Based on this support in the literature, age is hypothesized to be a significant covariate in the model.

4. Severity of injury measures were predicted to be significant moderators of the association between DRS recovery curves and performance on the PASAT at six months post-injury. Specifically, the less severe the injury, the flatter DRS recovery curves (smaller linear and curvilinear components) were predicted to be, and the smaller the intercept (the lower the DRS score) and the higher the PASAT score were expected to be, at six months post-injury.

This hypothesis is also well supported by the existing literature (Lezak et al. 2012) and consistent with the results of Ewing-Cobbs et al. (2004). Specifically, Ewing-Cobbs and colleagues reported that children who sustained a severe TBI performed worse on all achievement scores compared to children who sustained a mild or moderate TBI.

The severity of injury variables Best Day 1 GCS, pupillary responsivity, and Marshall CT scan classification have been related to outcome traditionally in our models (Biney 2010). The more severe the injury, the steeper the DRS recovery curves (larger linear and curvilinear components) were expected to be than the average of all the participants, due to greater possibility for improvement. Performance on the PASAT for participants with lower Best Day 1 GCS scores is currently unclear. Additionally, among our severity of injury variables, we predicted that Best Day 1 GCS (the highest GCS score achieved during the first 24 hours in the NICU) would be most likely to remain in the final model based on the findings of previous studies (Biney 2010).

Statistical Analyses

SPSS was used to run correlational matrices and plot raw data. Mplus was used to fit growth curve models to the data (Figure 3). The parameters of the best-fitting growth curve model were used as predictors of the PASAT score at six months post injury to address Hypotheses 1 and 2 (Figure 4). Age and severity of injury moderators were then added to the regression model to address Hypotheses 3 and 4 (Figure 5).

METHODS

Participants

This study received CPHS approval from the University of Houston (UH). Data for this archival study were collected originally in compliance with regulations mandated by the Institutional Review Board (IRB) of Baylor College of Medicine and by the UH CPHS. Permission to use the archival data was obtained from H. Julia Hannay, PhD, and Claudia S. Robertson, MD. Data from 91 participants with complicated mild, moderate and severe traumatic brain injury who were admitted to the Neurosurgery Intensive Care Unit (NICU) of a Level 1 Trauma hospital in Houston, Texas, were involved. Participants were excluded from the current study if they had a previous history of brain injury, a major psychiatric disorder, or if they sustained a gunshot wound to the head or other penetrating head injury. All participants spoke English fluently, as no audiotape of the Levin version of the PASAT was available in Spanish.

Inclusion in this study required that the participants be alive, not in a vegetative state, and were evaluated with the Disability Rating Scale at discharge from the acute care hospital, one, three and six months post-injury. Further, only participants who were able to complete the PASAT at six months post-injury following the standard procedure (n = 91) were included in the study. Participants who were unable to understand the test instructions were excluded from the study, as well as participants who did not complete the PASAT for other reasons, or participants whose test performance was determined to be unreliable.

Participant Demographics

Demographic information, including age, ethnic/cultural identity, gender and years of education, had been collected from patient and/or family/significant other reports and is presented in Table 1. The mechanism of injury for each patient was also collected and is represented in Table 2.

Procedure

Severity of Injury Measures

Severity of CHI measures were obtained from participants after admission to BTGH. These measures included the Best Day 1 Glasgow Coma Scale score, the pupillary reactivity score and the worst Marshall CT classification.

The Glasgow Coma Scale (GCS) was developed by Teasdale and Jennett (1974) to be a simple, standardized measure for evaluating the degree of altered consciousness or coma experienced by patients who have suffered brain injury. Three items comprise the GCS: eye opening (scored on a scale from 1-4), verbal response (1-5) and motor response (1-6). The total GCS score is the sum of the scores of the three items, and ranges from 3-15. A GCS scale of 3 indicates no eye, verbal or motor response, while a GCS score of 15 indicates full consciousness. (See Appendix D for GCS form). GCS scores were taken every hour while participants were in the NICU at BTGH. Best Day 1 GCS is the highest GCS obtained for each participant during the first 24 hours following admission to the NICU. The average Best Day 1 GCS score for the current sample was 8.11 (SD=3.70), with a range from 3-15 (Table 3).

Pupillary reactivity is another measure of CHI severity, taken at the same time as the Best Day 1 GCS score. Pupillary reactivity measures the speed at which the pupils constrict in response to direct light. Pupils are scored as either normal, sluggish (slow) or nonreactive. Pupillary reactivity is known to be associated with traumatic brain injury (Adoni & McNett 2007).

The Marshall CT classification system was developed by Marshall and colleagues in 1991 to categorize severity and type of abnormalities observed on CT brain scans (Table 3). There are six Marshall CT categories: Diffuse Injury I, Diffuse Injury II, Diffuse Injury III, Diffuse Injury IV, Evacuated mass lesion and Non-evacuated mass lesion (Marshall et al. 1991). Diffuse Injury I – IV are determined based on the status of the mesencephalic cisterns, the degree of midline shift (measured in millimeters), and the presence or absence of a mass or lesion. Diffuse Injury I is the least severe and refers to scans with no visible pathology, while Diffuse Injury IV is the most severe and refers to CT scans with a midline shift of more than 5 mm, and no high-density or mixed-density lesion larger than 25 cc. Diffuse Injury II and III fall between I and IV respectively with regard to degree of midline shift and size of lesion. An evacuated mass lesion is defined as any lesion surgically evacuated while a non-evacuated mass lesion is a high or mixed density lesion greater than 25cc that has not been surgically evacuated. The fact that the mass lesion has not been evacuated may mean that the consequences of evacuating it might be worse than not doing so. The current study will use the worst Marshall CT scan as a severity of injury variable, which represents the scan that reveals the largest amount of damage (degree of midline shift, size of lesion, etc.) across serial CT scans. Worst Marshall CT scan has been shown to correlate with functional outcome (Servadei et al. 2000).

In the current sample, three percent were classified as Diffuse Injury I, 43 percent as Diffuse Injury II, 22 percent as Diffuse Injury III, one percent as Diffuse Injury IV, 29 percent as non-evacuated mass lesion, and two percent as evacuated mass lesion (Table 3). See Appendix D for a detailed description of the Marshall CT classification.

DRS Evaluations

Participants had been evaluated with the Disability Rating Scale at one, three and six months post-injury, and at hospital discharge, a floating time point. The DRS was administered by a clinical neuropsychologist and/or her trained technicians who met weekly to quality control the data. The Disability Rating Scale (DRS) is a global outcome measure designed by Rappaport and colleagues (1982) to allow clinicians to quantitatively assess patients with severe head trauma at multiple times throughout the process of rehabilitation, so their progress could be measured from the coma state; through varying levels of awareness and functioning; and finally, to their return to the community. The DRS has also been used to evaluate patients who are less severely injured.

The DRS consists of eight items that fall within four categories. Each item is rated on scales of 0-3, 0-4 or 0-5, such that the sum of the highest scores on each item equal 29. Higher scores indicate a greater degree of impairment. A score of 30 is used to indicate death. The rationale is that it is easier to rate the degree of impairment than to rate the degree of intact functionality. DRS scores are often organized into seven categories. DRS scores of 0 are in the no disability category. DRS scores between 1 and 3 fall within the partial disability category. DRS scores between 4 and 6 fall in the moderate disability category. DRS scores between 7 and 11 fall within the moderately severe disability category. Scores between 11 and 16 fall within the severe disability category. Scores between 15 and 22 fall in the extremely severe disability category. Finally, scores between 21 and 28 fall within the vegetative state category. As demonstrated by the score ranges, the last four categories overlap with each other. Consequently, an individual's disability category cannot always be determined by DRS score alone, as a DRS score of 21 may fall into the vegetative state category, while another individual's score of 22 may fall into the extremely severe disability category. As a result, categorical analysis can be problematic when conducted on DRS scores. From patient information, it can be possible to determine whether any participants were misclassified in this categorical system. An alternative is to treat DRS scores as a continuous variable, similar to the McCauley et al. (2001) study.

The first category of the DRS is arousability, awareness and responsivity, and includes the following items: Eye Opening, Verbalization and Motor Response. This category is considered a modified GCS. Modifications include inverted numerical values to match the overall rating system of the DRS, as well as minor but important changes to measuring Verbalization. Eye Opening is rated on a scale of 0-3; Verbalization, or Best Verbal Response, is rated on a scale of 0-4, and Motor Response, specifically Best Motor Response, is rated on a scale of 0-5.The second category is cognitive ability for self-care functions, and is also comprised of three items, namely Feeding, Toileting and Grooming. Ratings made in this category take into account only the extent of the patient's knowledge of how to perform each of these items. These ratings do not reflect the patient's physical ability to perform these functions. Each item is rated separately on a scale of 0-3. The third category is dependence on others. This scale is adapted from Scranton, Fogel and Erdman (1970). It measures the individual's current level of physical dependency on others for completing tasks of daily living. Participants are rated on a scale from 0-5, where 0 reflects complete independence, and 5 suggests total dependence on others. The fourth and final category is psychosocial adaptability for school or work responsibilities that are required of an employee, homemaker or student. Also known as employability, this category is the most global measure of severity in the DRS. It measures the severity of an individual's cognitive and physical impairments with regard to their impact on the individual's ability to carry out responsibilities that are required of a student, employee or homemaker.

PASAT Administration

At six months post-injury, participants completed the Levin version of the PASAT (Levin et al. 1987) as part of a larger neuropsychological battery administered by a clinical neuropsychologist and/or her trained technicians. The Levin PASAT is comprised of four trials, and is administered in an audiotape format. During each trial, 50 digit cues were presented. Digits from one through nine were presented aurally in a random order. As the digits were presented, the participant was instructed to sum the two most recently presented consecutive digits, and to give the sum verbally. For example, if the digits three and then seven were presented, the participant would respond correctly by saying "ten." If the next digit presented was four, the correct response would become "eleven;" the new digit (four) was added to the most recent previous digit (seven), and not to a running total of the previous sum.

During each trial, the digits are presented at a precise interstimulus interval (ISI). The ISI changes across trials, such that each subsequent trial has a shorter ISI. The ISIs for the four respective trials are 2.4, 2.0, 1.6 and 1.2 seconds between each digit. Each trial was preceded with a recorded announcement stating that a new sequence was about to begin. Each trial was also separated from the following trial by a 15 second period of silence. The total number of responses for each trial is 49; consequently, the highest possible correct score is also 49. The highest possible correct score on the PASAT across trials is therefore 196. Performance on the PASAT results in three response types: correct responses, omissions and commissions. Correct responses (CR) occur when the patient gives the correct sum of the most recent two numbers presented. Omissions (OM) occur when the patient does not give any verbal response. Commissions (COM) occur when the patient provides an incorrect verbal response. Together, the sum of the three response types for each trial is always 49, such that: CR + OM + COM = 49 (see Appendix E).

RESULTS

All participants reliably completed the PASAT during their six month evaluation without interference from impairments that could affect task performance (e.g. language comprehension, hearing or oral expression impairments).

There were no missing data points for PASAT scores or the six month DRS scores, age, gender, racial/ethnic group, mechanism of injury or worst Marshall CT scan classification. Less than five percent of data points were missing from Best Day 1 GCS, and DRS scores at discharge, one month, and three months post-injury. Specifically, only one percent of data are missing from discharge and one month DRS time points. Three percent of data are missing from the three month time point. Approximately nine percent of data points were missing from the Best Day 1 pupillary reactivity scores. Because Best Day 1 pupillary reactivity was not the primary severity of injury variable of interest, it was dropped from growth curve analyses. The distribution of residuals did not drastically depart from normality.

Hypotheses 1 and 2

For all growth curve models, time was centered at one month post-injury to reduce multicollinearity created by high correlations between the linear and nonlinear terms. Intercepts, linear components and curvilinear components reported for all models consequently refer to the level and rate of change of DRS scores occurring at one month post-injury.

Raw DRS scores plotted across time points (Figure 6) suggested substantial curvilinearity. Scores declined over time and leveled off as they approached six months post-injury. At the first evaluation (either early discharge or one month post-injury), approximately 75 percent of participants had a DRS score between 7 and 26, placing them in either the moderately severe disability range (7-11), the severe disability range (11-16), the extremely severe disability range (15-22) or a vegetative state (21-28). Ten percent of participants were in a vegetative state, with DRS scores between 21 and 26. Initially, this percentage dropped rapidly; by three months post-injury, only 18 percent of participants had DRS scores greater than 7, which is a difference of 57 percentage points. None of the participants had a DRS score that was greater than 13. Scores between 7 and 13 place participants in either the moderately severe disability range or the severe disability range; none of the participants were still in a vegetative state by three months post-injury. Change in recovery then leveled out significantly between three and six months; at the six month DRS evaluation, four percent of participants still received a DRS score of 7 or higher from the total sample, which is only a 14 percentage point difference. All four percent of participants fell in the moderately severe disability range, with scores between 7 and 9.

These observations are reflected by the distribution of DRS scores at each time point (Appendix B). DRS scores were normally distributed at discharge. When divided into early discharge (before one month post-injury) and late discharge (after one month post-injury), DRS scores continued to be normally distributed. At one month post-injury, DRS scores were platykurtic; a greater percent of scores were present at both extremes of the DRS score range than would be expected by a normal distribution. This distribution is consistent with the observed significant initial drop in DRS scores; as participants' DRS scores decreased, middle scores decreased toward the lower end, thereby increasing the frequency of better recovery (i.e. the lowest scores in the left tail of the distribution). The highest scores also decreased to slightly lower scores, which then increased the frequency of those lower scores, located at the right tail of the distribution. This initial drop thereby created a different pattern of DRS frequencies across the sample. DRS scores at three and six months were positively skewed (Table 4), consistent with the observed significant decrease of participants with DRS scores of 7 or higher, and the decrease of the range of scores from 1 – 26 at early discharge, to 0 – 13 and 0 – 9 at three and six month DRS evaluations respectively.

To reflect these observations in the model, linear and curvilinear components were entered as random effects. A linear model, with only intercept and linear parameters, was applied first to the serial DRS scores. The quadratic model, which added the curvilinear parameter, was a significantly better fit, as demonstrated by a significant distributed chi square statistic (χ^2_4 = 265.04, $p = 0.001$). This model indicated that the intercept, linear component and curvilinear component were all significantly different from zero ($p < 0.001$) (Table 5). Significant random variation was observed for the intercept, linear component and curvilinear component ($p < 0.001$ for all components, Table 5). Significant covariation was observed between the intercept (i) and linear component (l) (cov (i, l) = -17.36, p < 0.001) (Table 5). The two parameters were inversely related, indicating that higher initial DRS scores covaried with steeper negative slopes. The curvilinear component (c) also covaried significantly with the intercept (cov (c, i) = 2.20, $p < 0.001$) and linear component (cov (c, l) = -1.20, $p < 0.001$). The intercept and curvilinear component were positively related, indicating that the higher the DRS score, the larger the curvilinear component. The linear component and curvilinear component were inversely related, indicating that steeper negative linear components were associated with larger positive curvilinear components. Based on this model, the expected level of the DRS score at one month post-injury was 10.63 and decreased by 4.58 points monthly, or 0.15 points daily (4.58/30 days). However, this rate of decrease slowed by 0.59 points per month squared, or 0.020 points per day squared (0.59/30 days), indicating that DRS curves decreased over time at a decreasing rate.

The PASAT performance variable, operationalized as the number of correct responses on the PASAT (PCR), was then added to the model to determine how PASAT performance at six months post-injury is related to the intercept, linear component and curvilinear component. Only the intercept of the DRS recovery curve was significantly associated with PCR at six months post-injury ($p = 0.001$, Table 6), and inversely related. This result suggested that the DRS score at one month post-injury was predictive of PASAT performance at six months post-injury, and that a higher intercept indicated worse PASAT performance. Neither the linear component nor the curvilinear component of the DRS recovery curve was found to be predictive of PASAT performance at six months post-injury. The observed DRS recovery curve model predicting to PCR is represented by Figure 7.

Hypotheses 3 and 4

The distribution of age in the sample was positively skewed (Table 1); a greater percent of individuals were at the younger end of the 15-59 age range than would be expected for a normal distribution. This skewed distribution is consistent with sampling methods, as only participants who were able to reliably complete the PASAT at six months were selected for the study. As higher age is strongly associated with worse outcomes **(**Lezak et al. 2012**)**, it is likely that fewer older individuals would be able to reliably complete the PASAT at six months post-injury than younger individuals. Best Day 1 GCS also had a positively skewed distribution

(Table 3); a greater percent of the current sample had lower GCS scores than would be expected for a normal distribution. This distribution is also consistent with sampling methods, as the levels of severity of participants in the sample - complicated mild, moderate or severe - are expected to be reflected by lower Best Day 1 GCS scores. Years of education was normally distributed throughout the sample (Table 1).

Correlational matrices revealed that age and years of education were significantly correlated (Pearson's $r = .317$, $p = 0.003$), but not significantly associated with any of the DRS scores, Best Day 1 GCS, or the PASAT correct responses (Table 7). Best Day 1 GCS score was found to be significantly correlated with PASAT correct responses (Pearson's $r = .309$, $p = 0.003$) (Table 7). Chi-square analyses revealed no significant relationships between the categorical predictors of gender, racial/ethnic group, mechanism of injury, or worst Marshall CT classification (Table 8).

Age, years of education and Best Day 1 GCS scores were transformed by subtracting the mean from each observation to reduce multicollinearity. PCR was transformed to a T score to reduce its variance. Each moderator variable was then entered separately into the DRS recovery curve model predicting to PCR (Tables 9 and 10). To assess the relationship between each moderator variable and the intercept, an interaction variable between the intercept and moderator was created and entered separately into the model. Relationships between the moderator variables and the linear and curvilinear components were not investigated because the intercept was the only parameter observed to be significantly associated with PCR. Initial attempts to run the models were met with error warnings generated by Mplus; a table of these warnings and their solutions can be found in Appendix C.

The interaction between age and intercept was significant ($p = 0.022$), demonstrating that age significantly moderated the relationship between the intercept and PASAT performance at six months post-injury (Table 9), which was consistent with expectations. Age and PCR were significantly associated ($\beta = -0.38$, $p = 0.028$), and inversely related, indicating that older participants had fewer PASAT correct responses at six months post-injury. Given that simple correlations between age and one month DRS score and age and PCR were nonsignificant (Table 6), this finding suggests that age significantly moderates the interaction between DRS score at one month and PASAT score at six months, but does not act on either variable directly.

None of the other individual interactions between the intercept and moderator variables were significant (Table 9 and 10). Further, no other modeled associations between the PCR and the other moderator variables were significant. The observed DRS recovery curve model predicting to PCR with age as the sole moderator is represented by Figure 8.

DISCUSSION

Statistical analyses revealed that contrary to the expectations outlined in Hypotheses 1 and 2, only the intercept of the DRS recovery curves significantly predicted PASAT performance at six months post-injury. This finding indicated that only the level of DRS score at one month post-injury, and not the trajectory of recovery, was predictive of later PASAT performance. Higher DRS scores, represented by larger intercepts, were associated with worse PASAT performance. Age was observed to moderate significantly the relationship between the intercept of the DRS recovery curve and PASAT performance at six months post-injury. This finding is partially consistent with Hypothesis 3. While age was found to be a significant moderator of the relationship between the DRS recovery curve and PASAT performance, the effect of age on the linear and curvilinear components of the recovery curves was not assessed due to the lack of observed relationship between these parameters and PASAT performance. The other demographic variables-gender, racial/ethnic group, and years of education-were not observed to moderate the relationship between the intercept of the DRS recovery curves and PASAT performance significantly. In contrast with Hypothesis 4, Best Day 1 GCS was not a significant moderator of the relationship between the intercept and PASAT performance. Finally, mechanism of injury and worst Marshall CT classification also were not found to significantly moderate the relationship between intercept and PASAT performance.

Predictive Utility of DRS Recovery Curves

The results corresponding with Hypotheses 1 and 2 contrasted notably with the findings of the McCauley et al. (2001) study. In the previous study, the linear and curvilinear components of the DRS recovery curves were significantly associated with the SO-perceived patient functioning. In the current study, only the intercept of the DRS recovery curves was significantly associated with cognitive performance at 6 months post-injury. The results of the previous study suggested that the rate of change of DRS scores over time was more important than the initial DRS score for predicting the SO's perception of the patient's cognitive, affective, or neurobehavioral outcomes. Conversely, the findings of the current study indicated that initial DRS score was more important than the rate of change of DRS scores over time for predicting cognitive performance at six months post-injury. Taken together, these findings demonstrate that DRS recovery curves can be used to predict both the patient's cognitive performance and the perceptions of the patient's significant other at six months post-injury. However, the mechanism of prediction differed greatly when DRS recovery curves were used to predict patient cognitive performance when DRS recovery curves were used to predict SO perception of patient functioning, as in the previous study.

Age as a Significant Moderator

In the current study, age was not directly correlated with either one month DRS score or six month PASAT. However, participant age was revealed to be a significant moderator of the relationship between DRS scores and PASAT performance. Specifically, older participants had higher initial DRS scores and performed worse on the PASAT at six months post-injury. This result is consistent with the existing TBI recovery literature, which has demonstrated that older adults improve less by one year post-injury than younger adults (Lezak et al. 2012). This result is also consistent with the well-supported finding that PASAT scores decrease as adults age (Tombaugh 2006).

Finally, this result is consistent with other models of TBI recovery incorporating the DRS. Biney (2010) sought to model the impact of blood alcohol level on DRS scores at one month post-injury using a linear multiple regression. Biney reported (2010) that when entered into the second step of the model, age was found to increase the amount of explained variance in DRS scores by seven percent above what was explained by severity of injury variables (R2change = .067, Fchange (1,334) =34.642,p <.0001.) Age was also found to increase the amount of explained variance in DRS scores beyond what was accounted for by severity of injury variables at three and six months post-injury, by nine percent (R2change = .087, Fchange (1,320) = 41.877, p <.0001.), and 12 percent (R2change = .123, Fchange (1, 264) = 48.365, p <.0001), respectively.

The current study did not find the other demographic variables to be significant moderators of the relationship between serial DRS scores and PASAT performance at six months post-injury. This finding is consistent with the results of some previous studies. PASAT performance is known to be unaffected by gender (Tombaugh 2006). Biney (2010) also did not find that ethnicity or gender contributed uniquely to the variance in DRS scores at one, three or six months post-injury.

Severity of Injury Variables

Severity of injury variables were not found to be significant moderators in the current study. These results were consistent with the Levin et al. (1990) study, which did not find first or worst postresuscitation GCS to be related to PASAT scores at one year post-injury. More generally, Sherman, Strauss and Spellacy (1997) reported nonsignificant associations between PASAT performance and other measures of head injury severity, including length of post-traumatic amnesia or length of loss of consciousness.

The results of the current study differed from previous cross-sectional models of the relationship between severity of injury variables and DRS scores. Biney (2010) modeled the ability of blood alcohol level to predict DRS scores with three separate linear regression models conducted at one, three, and six months post-injury. Across these cross-sectional models, Biney (2010) found Best Day 1 GCS to account for 28 percent of the variance of DRS scores (R2 = .281, F(1,335) = 132.517, p<.0001) at one month, 25 percent of the variance at three months (adjusted R2 = .245, F(1,321) = 105.385, p<.0001) and 20 percent of the variance at six months (R2 = .204, F(1, 265) = 69.027, p<.0001) post-injury. In the same study, Worst Marshall CT classification and Best Day 1 pupillary response together were found to account for three percent of the variance in DRS scores at one month post-injury (R2change = .033, Fchange (4,330) = 4.463,p =.002). Worst Marshall CT scan accounted for three percent of the variance in DRS scores at both three months post-injury (R2change = .025, Fchange (2,318) = 6.172, p =.002.) and at six months post-injury (R2change = .029, Fchange (2,262) = 5.899, p =.003).

However, the current study did not attempt to model the direct relationship between Best Day 1 GCS scores and DRS scores. Instead, the current study only modeled the ability of Best

Day 1 GCS scores to moderate the relationship between DRS scores and PASAT performance. Further, Biney's (2010) results were consistent with the significant correlations between Best Day 1 GCS scores and DRS scores at discharge, one and three months post-injury reported by the current study. Taken together, these results suggest that Best Day 1 GCS scores may have strong direct correlations with cross-sectional DRS scores, but do not moderate the relationship between DRS recovery curves and later cognitive performance.

Study Limitations and Future Directions

Certain limitations of the current study design remain to be addressed. The sample size was not particularly large, but is consistent with other previous studies of the DRS, which have ranged in sample size from 28 to 393 (Hall, Cope & Rappaport 1985; Gouvier et al. 1987; Giacino et al. 1991; Hall et al. 1993; Choi et al. 1998; McCauley, Hannay and Swank 2001; Armstrong 2010; Biney 2010). A significant percent of missing data precluded inclusion of Best Day 1 pupillary reactivity in the models as a moderator variable. A future study with more complete Best Day 1 pupillary reactivity data could be conducted to elucidate the effect of this severity of injury variable on the relationship between DRS recovery curves and PASAT performance.

The PASAT was chosen as the cognitive performance outcome variable due to its demonstrated sensitivity to TBI-associated cognitive changes. However, its status as a cognitively demanding task necessarily limited the study sample so that only those participants who were able to complete the PASAT reliably at six months post-injury. Reliable completion of the PASAT at six months as an inclusion criterion may have depressed the average DRS scores of the study sample for later DRS evaluations, as participants who are less globally impaired by six months post-injury (i.e. with lower DRS scores) would be more likely to reliably complete the PASAT. The result is a study sample of participants who have achieved lower levels of disability by six months post-injury than would have been observed in the general sample. Visual inspection of DRS score distributions (Appendix B) and visual comparisons between the DRS scores plotted across time for the current study (Figure 5) and for the McCauley et al. (2001) study (Figure 2) supported this observation. Because all participants reached such a small range of DRS scores by six months post-injury, it follows that the rate of change of DRS scores over time would not be as predictive of PASAT scores as initial DRS scores alone.

To address this limitation, future studies could apply the methodology of the current study to other neuropsychological measures. Processing speed is one cognitive domain known to be sensitive to CHI (Lezak et al. 2012). Some measures of processing speed, while still sensitive to CHI, are less cognitively demanding than the PASAT, and therefore could be completed by participants with a wider range of global functioning levels at later time points post-injury. Such potential outcome measures include the Trail Making Test Parts A and B, Symbol Digit Search, Wechsler Symbol Search and Coding subtests, the Stroop color and word trials, or the color and word-reading trials of the Color-Word Interference Test from the Delis-Kaplan Executive Function System.

Another way to address this limitation would be to predict to PASAT completion codes rather than outright performance. The study methodology permits the prediction of DRS recovery curves to categorical variables as well as continuous variables. As previously described, all participants in the current study completed the PASAT reliably. Inclusion of participants to the study sample who attempted the PASAT but could not complete it for various reasons would likely result in increased ranges of DRS scores at later time points post-injury.

Finally, data from the current study demonstrated an interesting relationship between the six month DRS and the six month PASAT. Even though the variance of DRS scores was the smallest at the six month time point (Table 4), it also shared the greatest covariance with six month PASAT scores (Table 7). One reason for this finding is that the DRS at six months most closely represented a participant's level of impairment at the time of PASAT administration, and therefore is more strongly related to PASAT performance than DRS scores at other time points. To follow this reasoning further, all the models from the current study could be re-centered at either three months or at six months post-injury. Re-centering would move the intercept of the model from one month DRS score to either three or six month DRS score. The resulting estimates could be compared to those of the current study to determine whether re-centering the model would create a better fit.

Summary

The change of DRS scores over time was fit best by a quadratic growth curve model with random intercept, linear and curvilinear parameters. However, the utility of these DRS recovery curves for predicting PASAT performance at six months post-injury was limited to a single significant association observed between initial DRS score and PASAT performance. In other words, only initial DRS scores were predictive of later cognitive performance. Age was found to be a significant moderator of the relationship between initial DRS scores and PASAT performance. No other demographic or severity of injury variables were significant moderators. Future research may include evaluation of the ability of DRS recovery curve parameters to predict performance on less cognitively demanding neuropsychological measures.

APPENDICES

APPENDIX A Figures and Tables

Figure 1. Ewing-Cobbs et al. (2004) Growth Curve Table for WRAT Arithmetic Scores.

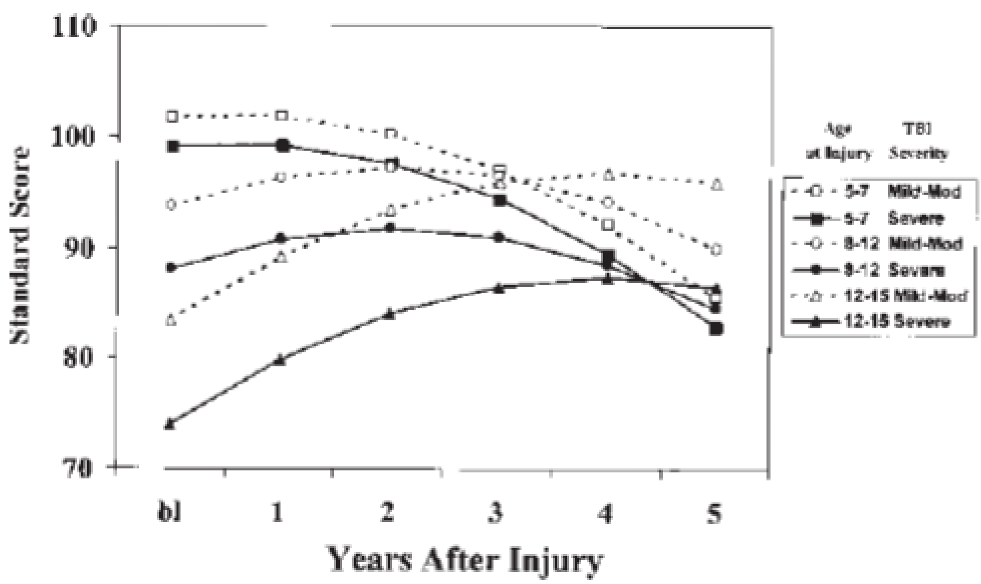


Fig.1. Growth curves grouped by age at injury and TBI severity for WRAT Arithmetic scores from the Ewing-Cobbs et al. (2004) study are shown above. The model with a random intercept, a random linear component and a fixed curvilinear component best fit the data. A significant covariation was found between the intercept and linear component, which suggested faster rates of score increases for children with lower scores at one year post-injury than for children with higher scores. Addition of age at injury showed that older children had lower initial scores, but their scores accelerated more over time than the scores of younger children.

Figure 2. McCauley et al. (2001) Individual DRS Recovery Curves

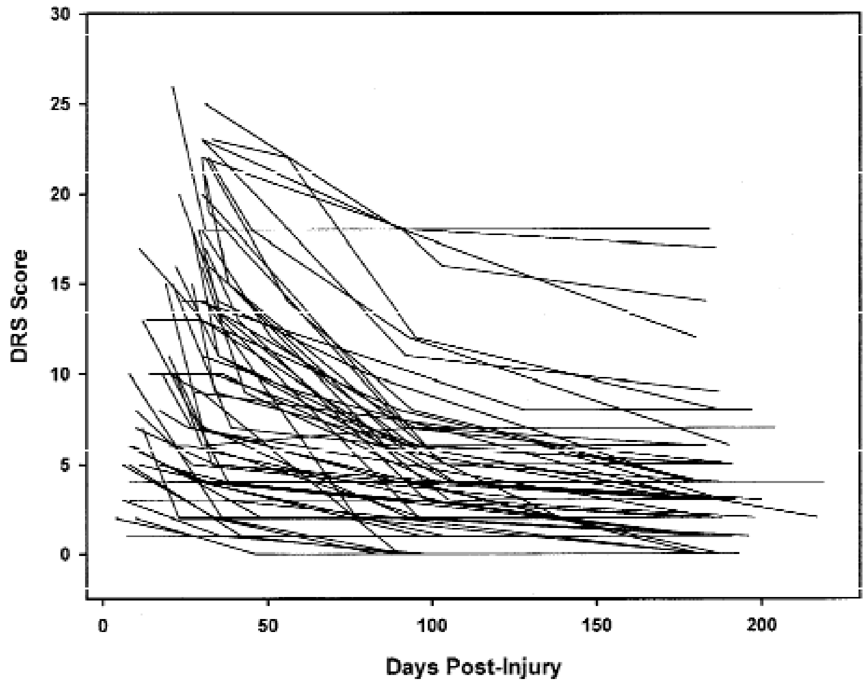


Fig. 1. *Individual DRS recovery curves*: This figure illustrates individual Disability Rating Scale recovery curves i aggregate for 55 participants.

Figure 3. The Expected Quadratic Model.

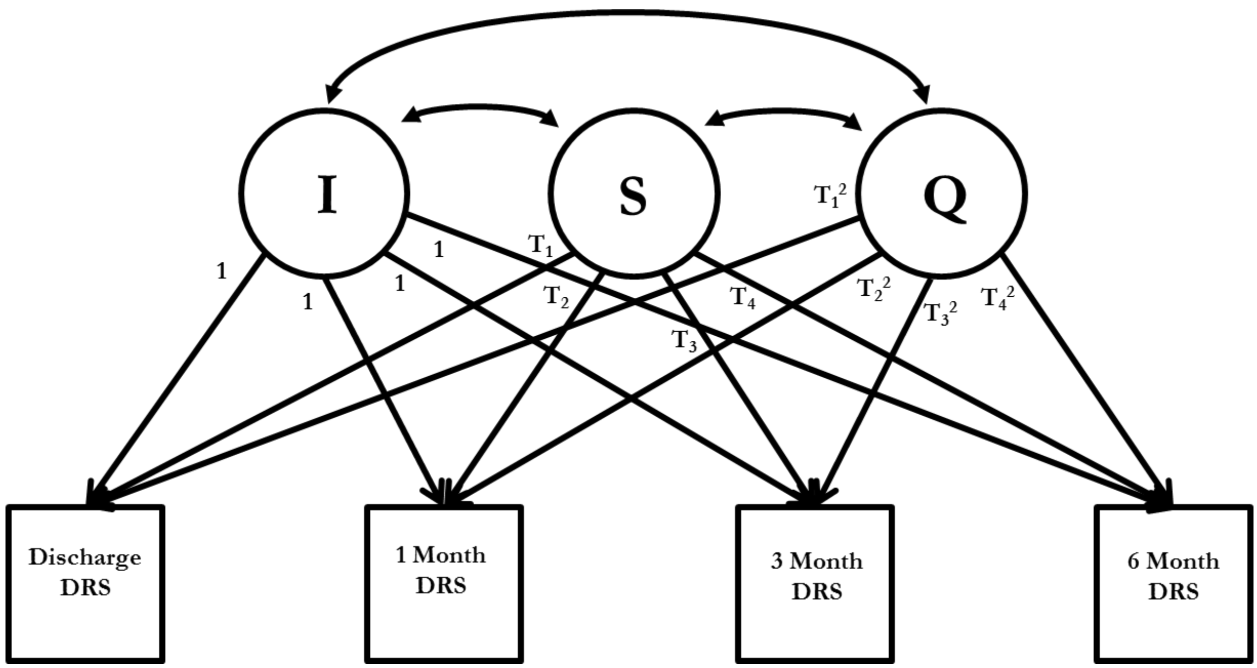


Fig.3. I: intercept; S: slope or linear component; Q: quadratic or curvilinear component. 1, T_1 and T_1^2 represent the parameter estimates for the intercept, linear and curvilinear components respectively. The intercept parameter estimate was fixed as a constant (1). All parameter estimates were random and permitted to vary within the model.

Figure 4. The Expected Quadratic Model Predicting to Six Month PASAT Score.

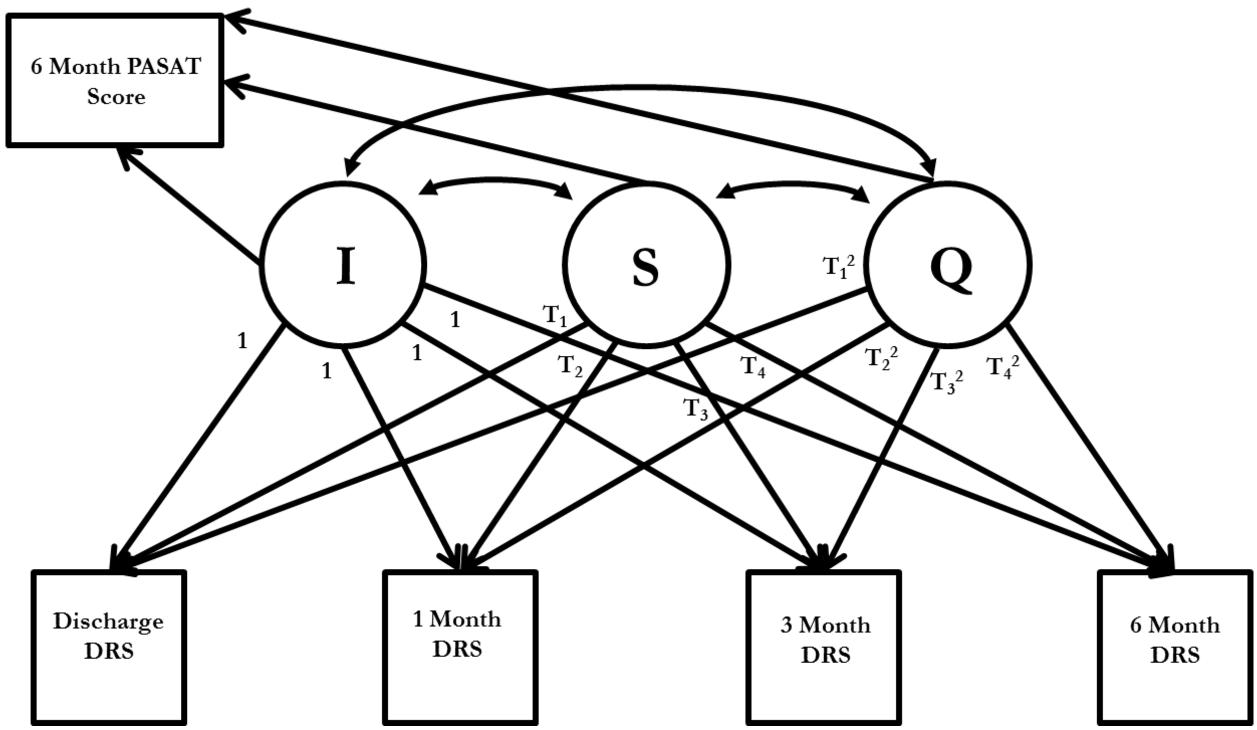


Fig.4. I: intercept; S: slope or linear component; Q: quadratic or curvilinear component. 1, T_1 and T_1^2 represent the parameter estimates for the intercept, linear and curvilinear components respectively. The intercept parameter estimate was fixed as a constant (1). All parameter estimates were random and permitted to vary within the model. This model incorporated the PASAT scores as the outcome variable. The ability of the intercept (I), linear component (s) and curvilinear component (Q) for predicting six month PASAT performance was each evaluated separately.

Figure 5. The Expected Effect of Moderator Variables on the Quadratic Model Predicting to Six Month PASAT Score.

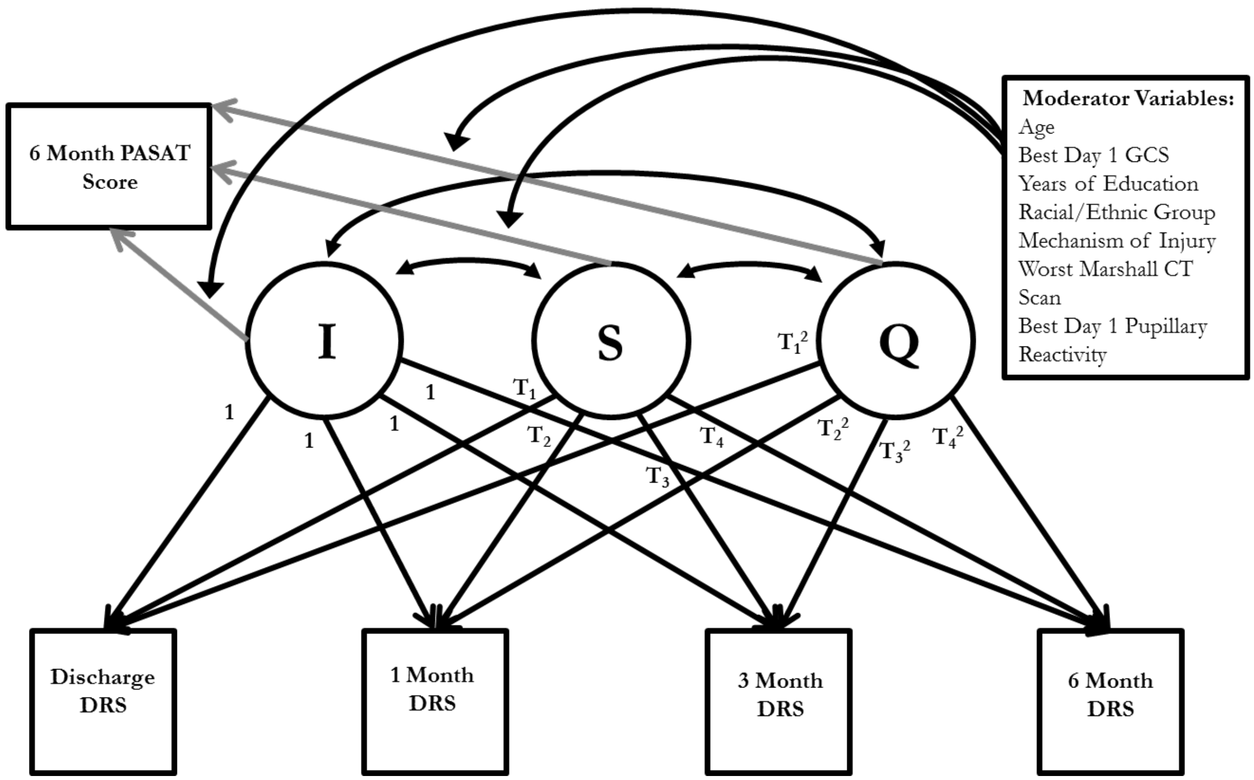


Fig.5. I: intercept; S: slope or linear component; Q: quadratic or curvilinear component. 1, T_1 and T_1^2 represent the parameter estimates for the intercept, linear and curvilinear components respectively. The intercept parameter estimate was fixed as a constant (1). All parameter estimates were random and permitted to vary within the model. This model demonstrates the planned analyses of the effects of each moderator variable (listed in the box at the top right) on the predictive relationships between each parameter estimate (I, S and Q) and six month PASAT performance.

Figure 6. Raw Disability Rating Scale Scores Across Time Points.

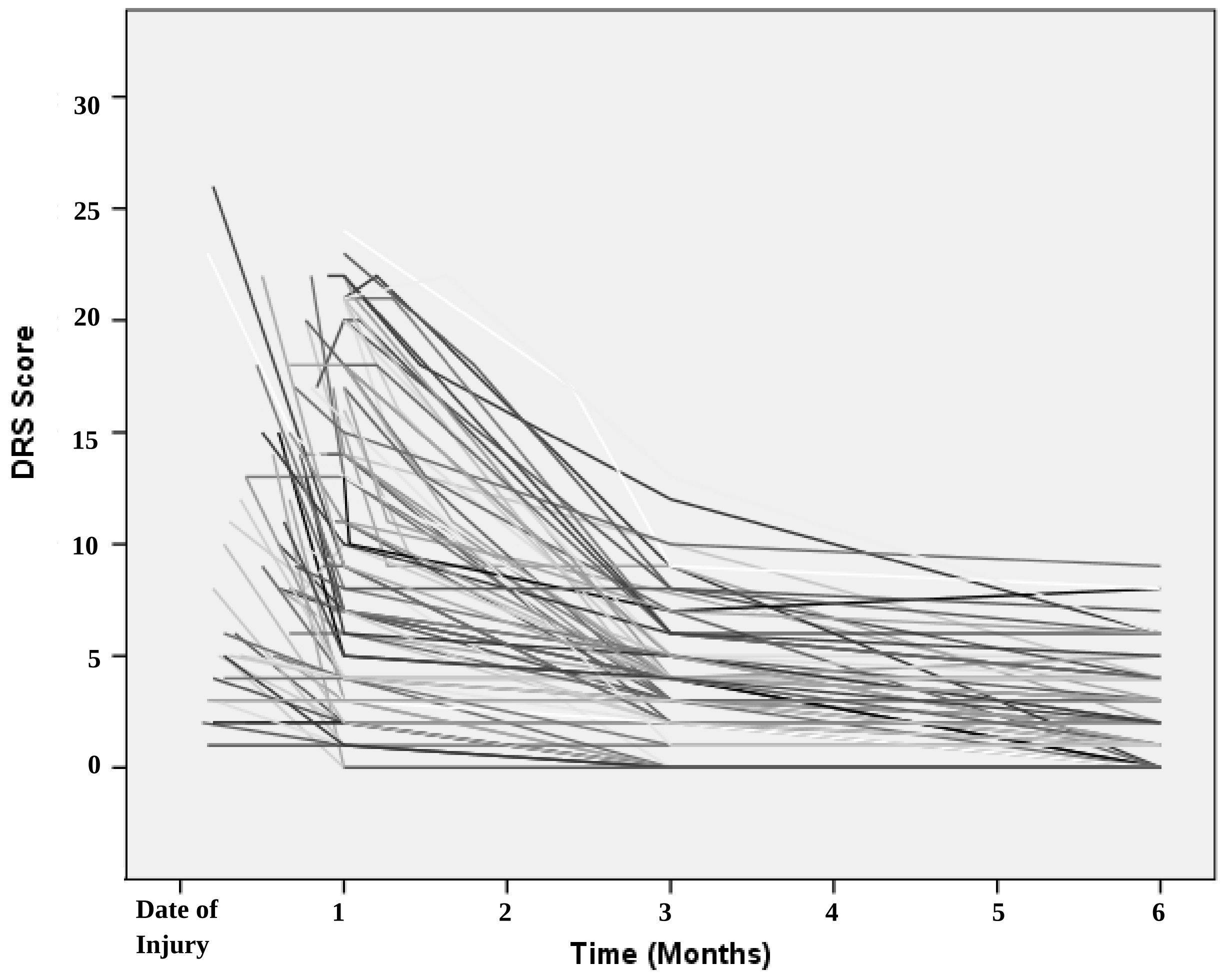


Fig.6. This figure shows the raw DRS scores plotted across all time points for each participant.

Figure 7. The Observed Model Predicting to PASAT Correct Responses at 6 Months Post-Injury.

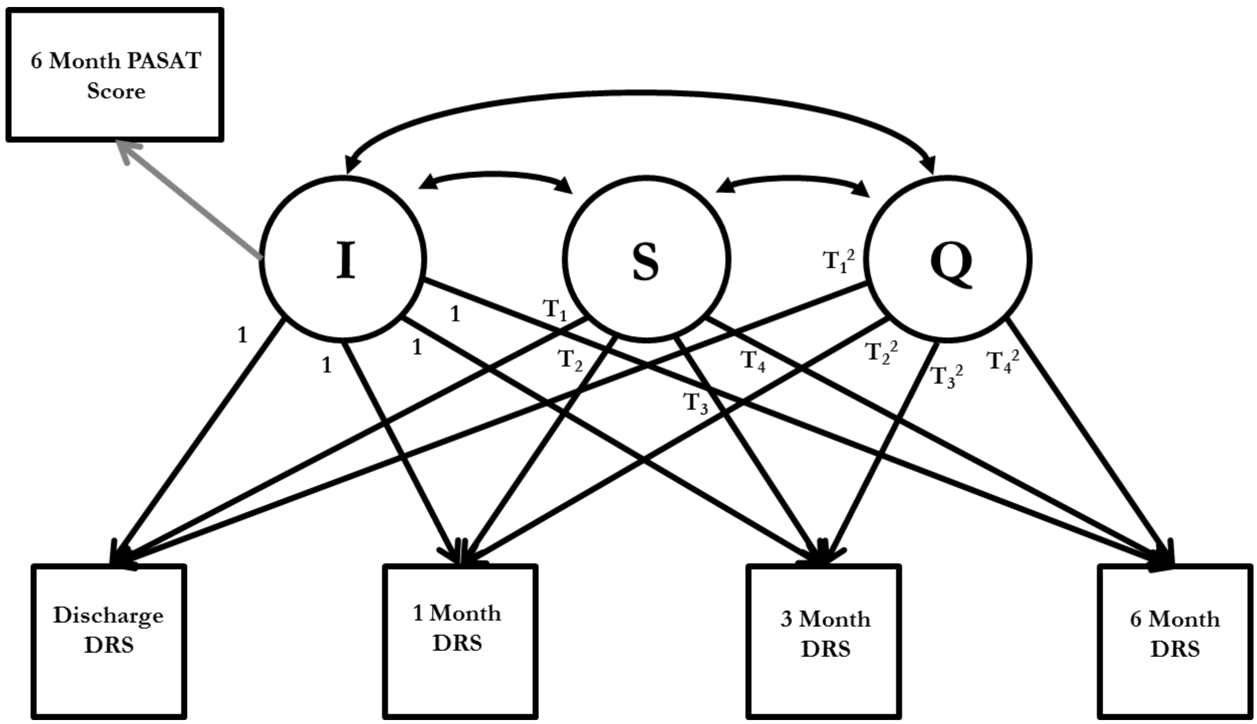


Fig.7. I: intercept; S: slope or linear component; Q: quadratic or curvilinear component. 1, T_1 and T_1^2 represent the parameter estimates for the intercept, linear and curvilinear components respectively. The intercept parameter estimate was fixed as a constant (1). All parameter estimates were random and permitted to vary within the model. This model shows the observed significant relationship between each parameter estimate (I, S and Q) and six month PASAT performance. Only the intercept (I) was significantly associated with six month PASAT performance.

Figure 8. The Observed Model with Moderator Variables.

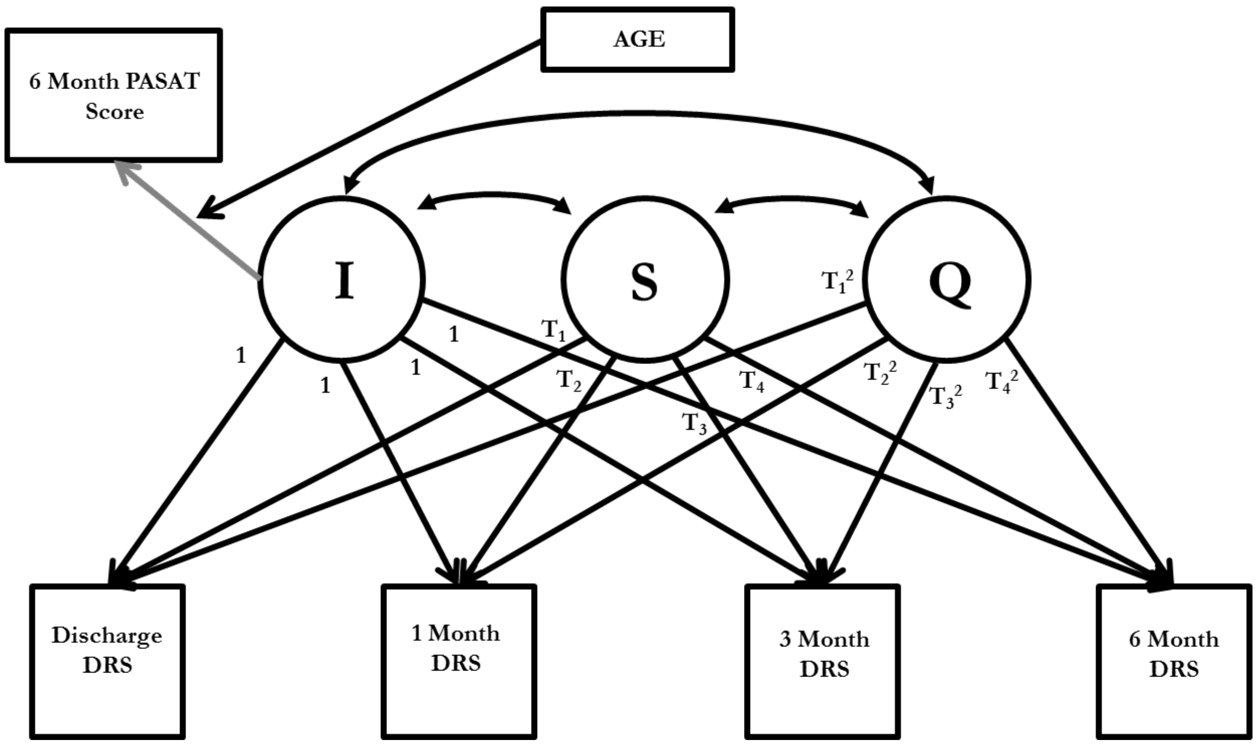


Fig.8. I: intercept; S: slope or linear component; Q: quadratic or curvilinear component. 1, T_1 and T_1^2 represent the parameter estimates for the intercept, linear and curvilinear components respectively. The intercept parameter estimate was fixed as a constant (1). All parameter estimates were random and permitted to vary within the model. This model shows the observed significant relationship between the intercept and six month PASAT performance, and incorporates age as the only observed significant moderator variable of this relationship.

Table 1. Participant Demographics.

Demographics	**Mean (years)**	**StDev (years)**	**Range (years)**	**Skewness**	**Skewness /SE**	**Kurtosis**	**Kurtosis /SE**
Age	29.79	11.73	15-59	0.747	**2.955283***	-0.354	-0.7079
Years of Education	11.77	2.67	6-20	0.172	0.668662	0.328	0.644373
	N	**Percent**					
Ethnic/Cultural Identity							
Non-Hispanic White	48	52.7%					
Hispanic	26	28.6%					
Black	17	18.7%					
Gender							
Male	71	78.%				-	
Female	20	22%				-	

StDev: standard deviation; SE: standard error; ***** p **< 0.05**.

Table 2. Mechanisms of Injury.

Mechanism of Injury	N	Percent
MVA	46	50.5%
Assault/Fight	14	15.4%
Fall/Jump	10	11.0%
MCA	9	9.9%
Auto-Pedestrian	4	4.4%
Recreational Vehicle	3	3.3%
Other	3	3.3%
Unknown	2	2.2%

MVA: motor vehicle accident; MCA: motorcycle accident; StDev: standard deviation.

Table 3. Severity of CHI in the Sample.

Measures	Mean	StDev	Range	Skewness	Skewness /SE	Kurtosis	Kurtosis /SE
Best Day 1 GCS Score	8.11	3.70	3-15	.666	**2.591873***	-.515	-1.01383
			N	**Percent**			
Worst Marshall CT Classification							
Diffuse Injury I			3	3.3%			
Diffuse Injury II			39	42.9%			
Diffuse Injury III			20	22%			
Diffuse Injury IV			1	1.1%			
NE-ML			26	28.6%			
EML			2	2.2%			

GCS: Glasgow Coma Scale; StDev: standard deviation; SE: standard error. *** p < 0.05**.

Table 4. Descriptive Statistics for Serial DRS Evaluations and PASAT Correct Responses.

		DRS Discharge	1 Month DRS	3 Month DRS	6 Month DRS	PASAT Correct Responses
N	**Valid**	90	90	88	91	91
	Missing	1	1	3	0	0
Mean		11.500	9.844	3.841	2.385	102.989
Std. Deviation		6.1265	7.0486	2.8563	2.1384	36.1922
Range		1 - 26	0 - 24	0 - 13	0 - 9	27 - 180
Skewness		.269	.424	.800	.877	.009
Skewness/SE		1.059055	1.669902	**3.115391***	**3.47154***	0.035427
Kurtosis		-.896	-1.138	.847	.428	-.678
Kurtosis/SE		-1.781312	**-2.26257***	1.665832	0.85631	-1.3545

SE: standard error. * ($p < 0.05$).

Table 5. Linear and Quadratic DRS Recovery Curve Models.

Model			Parameter Estimate	Estimate/SE	*p*
Linear					
	Intercept	Mean	9.05	11.44	**0.000**
		Variance	28.56	4.80	**0.000**
	Linear Component	Mean	-1.34	-7.54	**0.000**
		Variance	0.77	4.31	**0.000**
	Covariance	Intercept x Linear	-4.37	-3.87	**0.000**
Quadratic					
	Intercept	Mean	10.63	12.52	**0.000**
		Variance	39.22	8.29	**0.000**
	Linear Component	Mean	-4.58	-9.84	**0.000**
		Variance	9.06	1.58	**0.000**
	Curvilinear Component	Mean	0.59	8.96	**0.000**
		Variance	0.16	4.60	**0.000**
	Covariance	Intercept x Linear	-17.36	-7.07	**0.000**
		Intercept x Curvilinear	2.20	6.18	**0.000**
		Linear x Curvilinear	-1.20	-5.09	**0.000**

SE: standard error. **BOLD** indicates significant *p* values.

Table 6. Summary of DRS Recovery Curve Models for Hypotheses 1 and 2

Model	Parameter Estimate	Estimate/SE	*p*
Predicting to PASAT Correct Responses (PCR)			
Intercept to PCR	-9.03	-3.40	**0.001**
Linear Component to PCR	-43.26	-1.68	0.093
Curvilinear Component to PCR	-228.03	-1.42	0.156

PCR: PASAT correct responses; SE: standard error. **BOLD** indicates significant *p* values.

Table 7. Pearson Correlation Coefficient Matrix for Serial DRS Evaluations, PASAT Scores and Continuous Moderator Variables.

	Age	**Years of Education**	**Best Day 1 GCS Score**	**Discharge DRS**	**1 Month DRS**	**3 Month DRS**	**6 Month DRS**	**6 Month PASAT**
Age	1							
Years of Education	**.317** ***p*=0.003**	1						
Best Day 1 GCS Score	.190 *p*=0.077	.084 *p*=0.447	1					
Discharge DRS	-.144 *p*=0.175	.018 *p*=0.865	**-.540** ***p*<0.001**	1				
1 Month DRS	-.053 *p*=0.622	-.077 *p*=0.476	**-.430** ***p*<0.001**	**.672** ***p*<0.001**	1			
3 Month DRS	.026 *p*=0.811	-.097 *p*=0.378	**-.297** ***p*=0.006**	**.532** ***p*<0.001**	**.731** ***p*<0.001**	1		
6 Month DRS	.122 *p*=0.251	-.075 *p*=0.486	-.153 *p*=0.156	**.326** ***p*=0.002**	**.586** ***p*<0.001**	**.723** ***p*<0.001**	1	
6 Month PASAT	-.103 *p*=0.333	.067 *p*=0.537	**.309** ***p*=0.003**	**-.360** ***p*<0.001**	**-.446** ***p*<0.001**	**-.479** ***p*<0.001**	**-.483** ***p*<0.001**	1

BOLD indicates significant *r* and *p* values.

Table 8. Chi Square Analyses Matrix.

	Gender	Race/Ethnicity	Mechanism of Injury	Worst Marshall CT
Gender	1			
Race/Ethnicity	1.878 $p = 0.391$	1		
Mechanism of Injury	10.731 $p = 0.151$	18.617 $p = 0.180$.	1	
Worst Marshall CT	4.153 $p = 0.528$	6.700 $p = 0.753$.	42.413 $p = 0.182$	1

Table 9. Summary of DRS Recovery Curve Models with Moderating Demographic Variables.

Models with Moderator Variables	Parameter Estimate	Estimate/SE	*P*
Age			
Intercept to PCR	-2.89	-2.85	**0.004**
Linear Component to PCR	-16.55	-1.82	0.069
Curvilinear Component to PCR	-92.32	-1.70	0.090
Intercept*Age Interaction to PCR	0.029	2.29	**0.022**
Age to PCR	-0.38	-2.20	**0.028**
Years of Education (EdYr)			
Intercept to PCR	-7.49	-3.01	**0.003**
Linear Component to PCR	-21.09	-0.70	0.482
Curvilinear Component to PCR	-79.26	-0.40	0.685
Intercept*EdYR Interaction to PCR	0.173	0.80	0.426
EdYr to PCR	-1.25	-0.60	0.552
Gender			
Intercept to PCR	-11.30	-3.52	**0.000**
Linear Component to PCR	-53.50	-1.94	0.053
Curvilinear Component to PCR	-289.47	-1.68	0.093
Intercept*Gender Interaction to PCR	0.816	0.66	0.510
Gender to PCR	7.79	0.44	0.664
Racial/Ethnic Group (ECI)			
Intercept to PCR	-8.77	-2.84	**0.004**
Linear Component to PCR	-48.12	-1.71	0.088
Curvilinear Component to PCR	-261.32	-1.50	0.134
Intercept*Age Interaction to PCR	-0.20	-0.53	0.596
ECI to PCR	-1.73	-0.36	0.716

PCR: PASAT correct responses; SE: standard error. **BOLD** indicates significant *p* values.

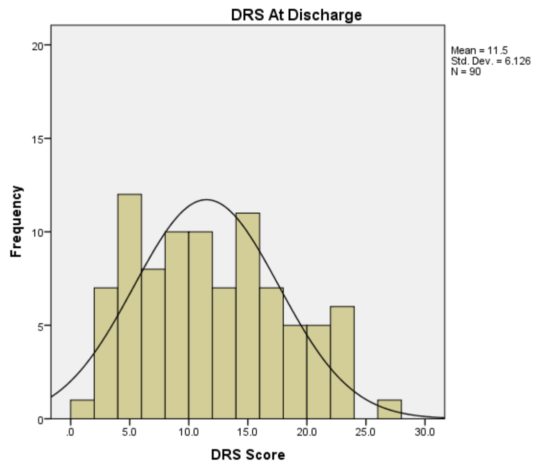
Table 10. Summary of DRS Recovery Curve Models with Severity of Injury Moderating Variables.

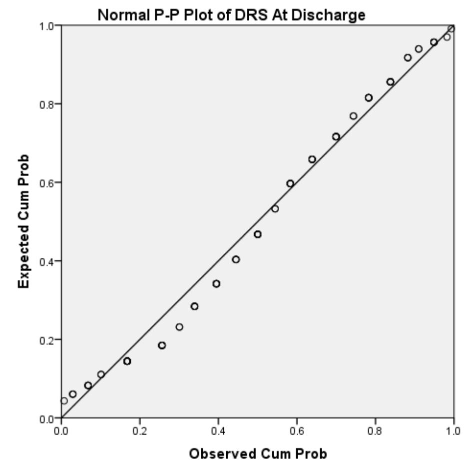
Models with Moderating Variables	Parameter Estimate	Estimate/SE	*p*
Best Day 1 Glasgow Coma Scale (GCS)			
Intercept to PCR	-9.99	-3.327	**0.001**
Linear Component to PCR	-54.53	-1.91	0.056
Curvilinear Component to PCR	-290.32	-1.65	0.100
Intercept*GCS Interaction to PCR	-0.03	-0.21	0.835
GCS to PCR	2.00	1.172	0.241
Worst Marshall CT Classification (MCTW)			
Intercept to PCR	-9.52	-3.06	**0.002**
Linear Component to PCR	-40.43	-1.53	0.126
Curvilinear Component to PCR	-211.20	-1.27	0.204
Intercept*MCTW Interaction to PCR	0.27	0.56	0.574
MCTW to PCR	-7.89	-1.55	0.121
Mechanisms of Injury (MOI)			
Intercept to PCR	-9.25	-3.14	**0.002**
Linear Component to PCR	-46.39	-1.70	0.089
Curvilinear Component to PCR	-249.30	-1.47	0.143
Intercept*MOI Interaction to PCR	-0.047	-0.18	0.855
MOI to PCR	-1.35	-0.47	0.642

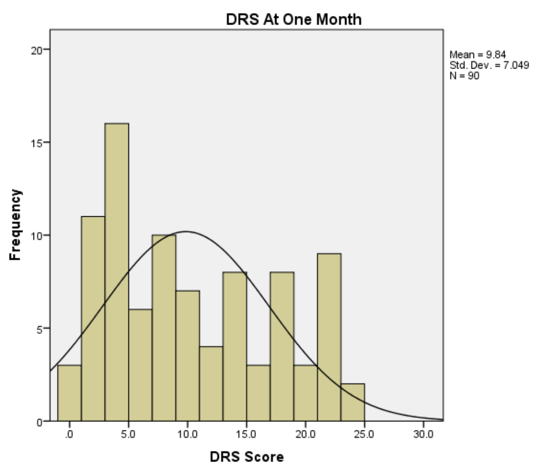
PCR: PASAT correct responses; SE: standard error. **BOLD** indicates significant *p* values.

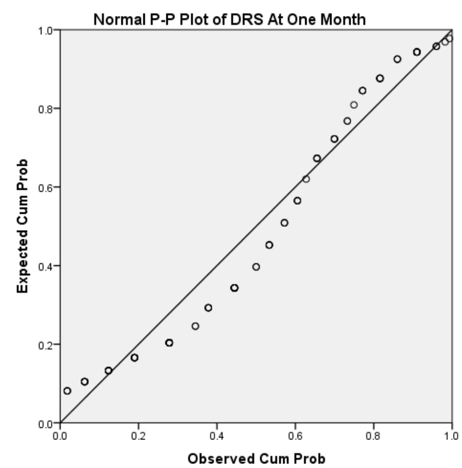
APPENDIX B Distribution Histograms and P-P Plots

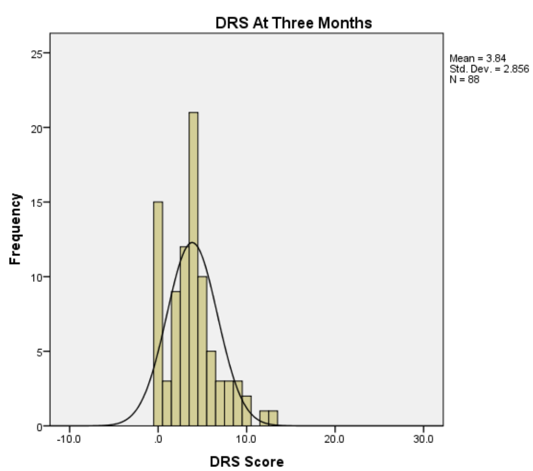
Serial DRS Evaluation Distributions

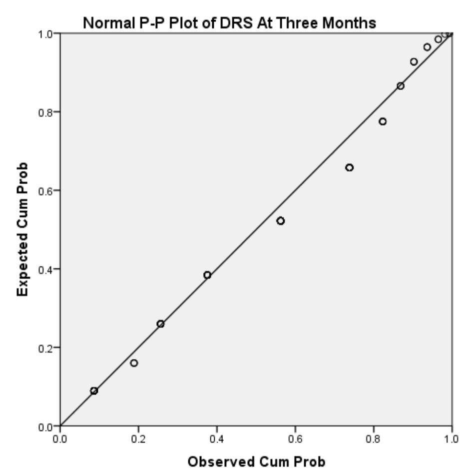


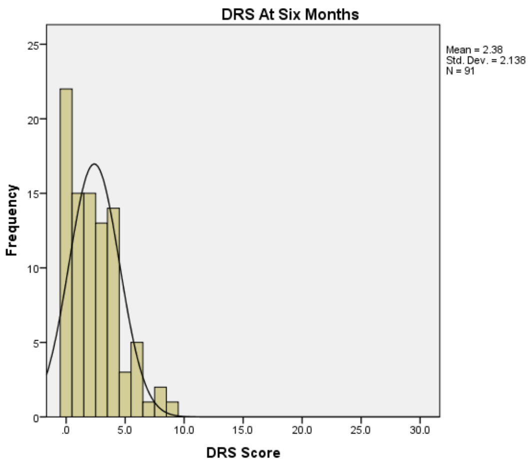


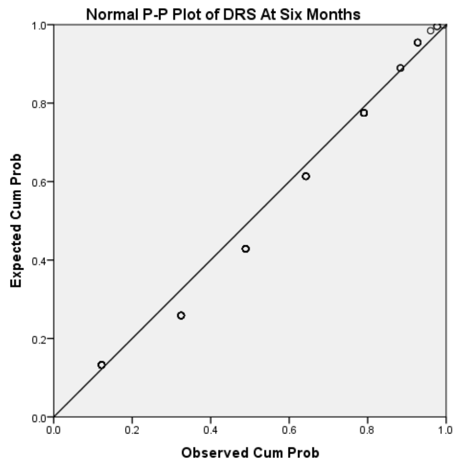




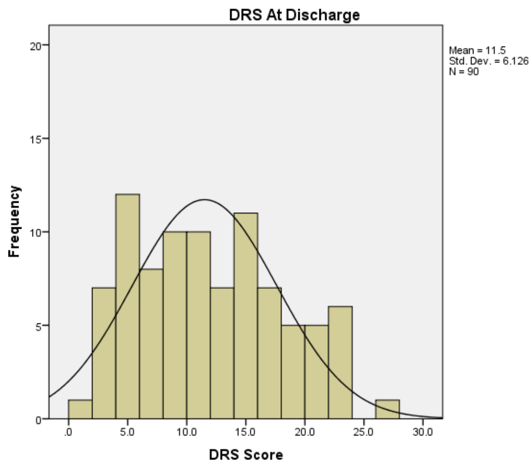


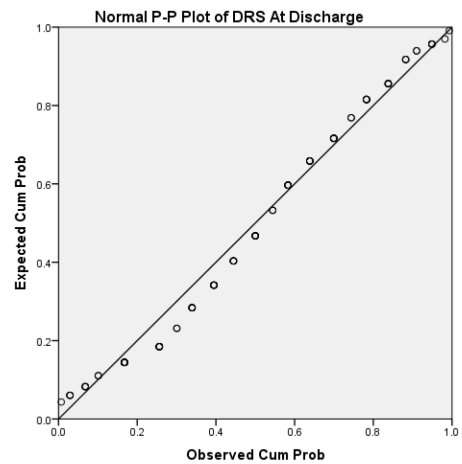


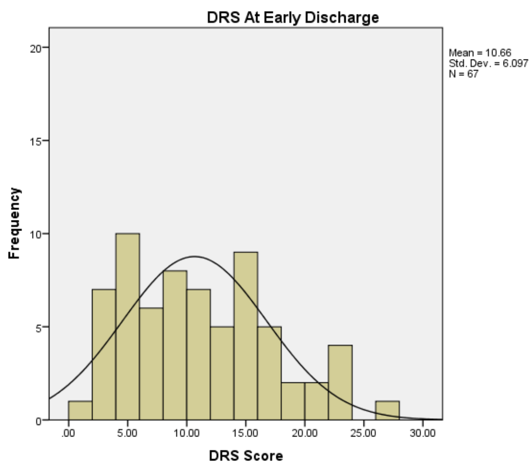

DRS At Six Months
Mean = 2.38
Std. Dev. = 2.138
N = 91
Frequency
DRS Score

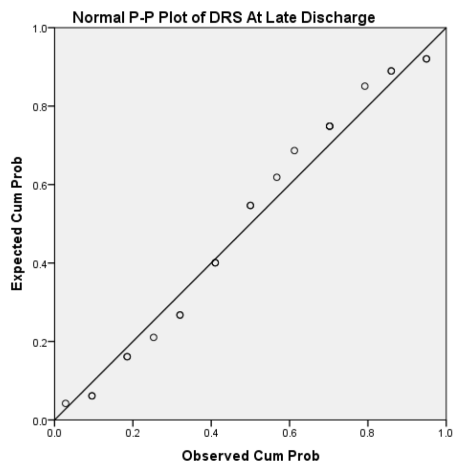

Normal P-P Plot of DRS At Six Months
Expected Cum Prob
Observed Cum Prob

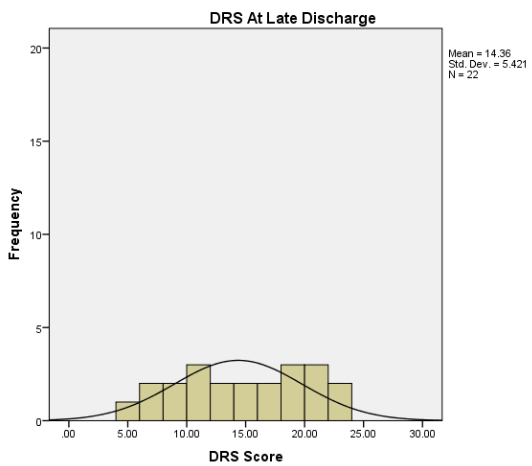
Comparison of DRS Score by Discharge Timing

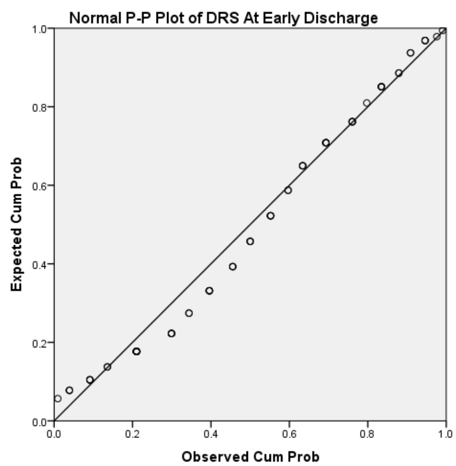




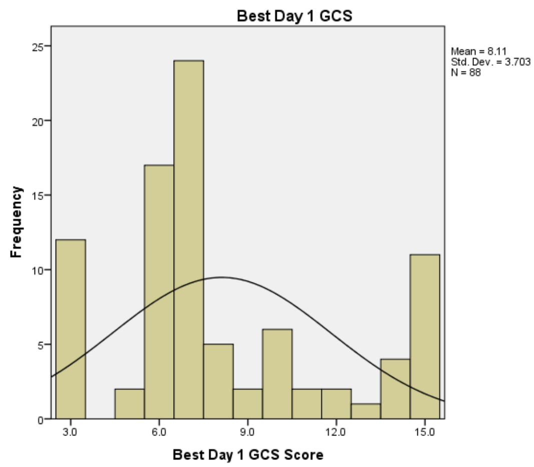


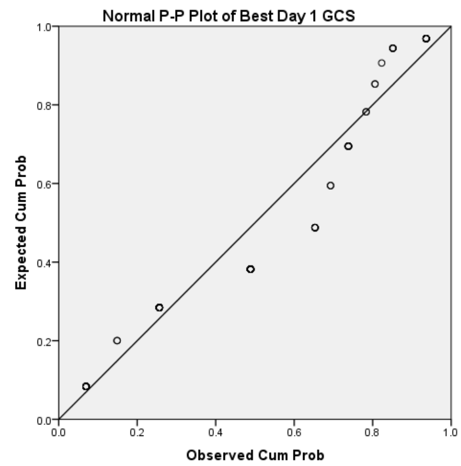


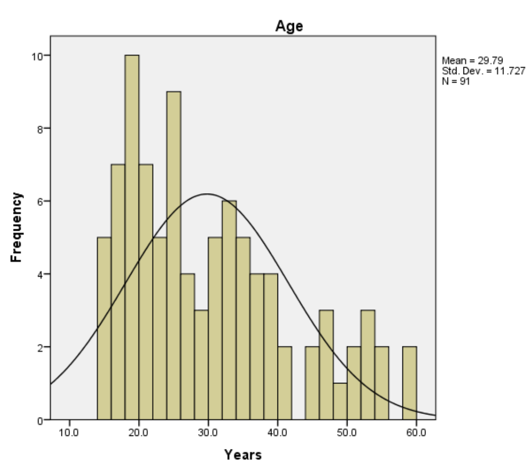


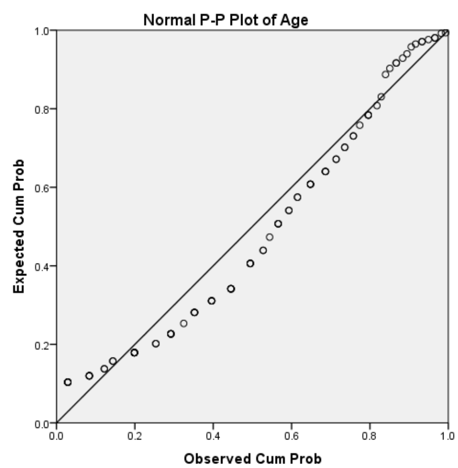


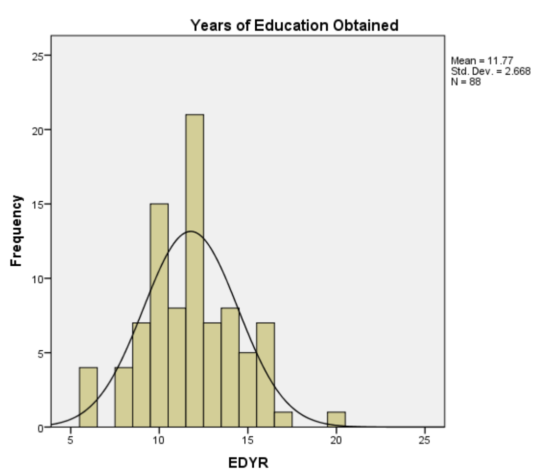
Best Day 1 GCS, Age and Years of Education Distributions

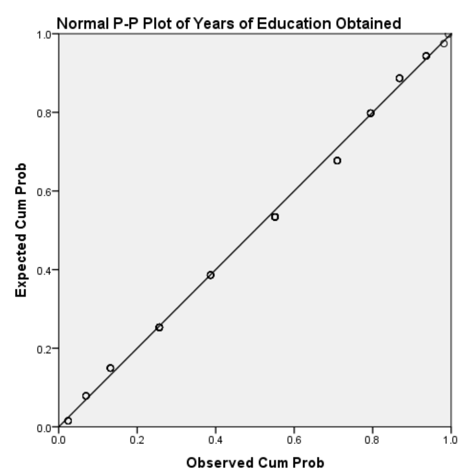




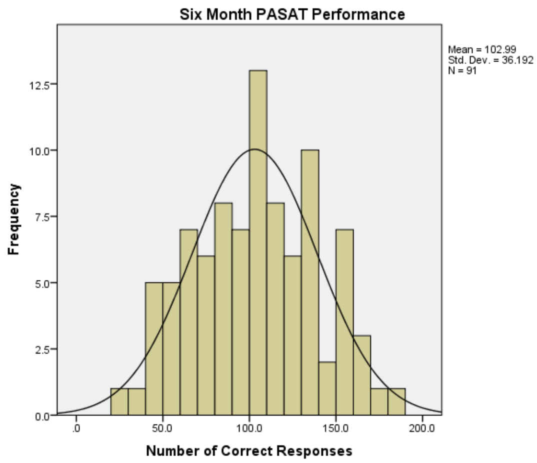


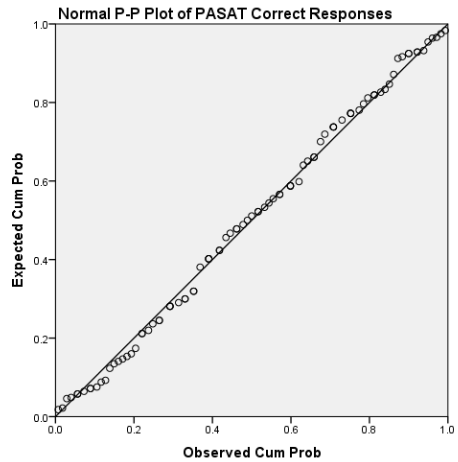






PASAT Correct Responses Distribution





APPENDIX C Error Problem-Solving in Mplus

<table>
<tr><th>Mplus Warning</th><th>Solution</th></tr>
<tr><td>A) THE MODEL ESTIMATION HAS REACHED A SADDLE POINT OR A POINT WHERE THE OBSERVED AND THE EXPECTED INFORMATION MATRICES DO NOT MATCH. AN ADJUSTMENT TO THE ESTIMATION OF THE INFORMATION MATRIX HAS BEEN MADE.
THE CONDITION NUMBER IS ******.
THE PROBLEM MAY ALSO BE RESOLVED BY DECREASING THE VALUE OF THE MCONVERGENCE OR LOGCRITERION OPTIONS OR BY CHANGING THE STARTING VALUES OR BY USING THE MLF ESTIMATOR.</td><td rowspan="2">Initial addition of the PASAT score as the outcome variable to the quadratic model observed in Table 5 resulted in Warning A.

1) Use of the MLF Estimator instead resulted in Warning B.

With the MLR Estimator, Warning A was finally eliminated using all of the following adjustments to the Mplus code:

1) Parameter estimates from the initial quadratic model (Table 5) were entered as starting variables for all models with the outcome and moderator variables.

2) The means of all moderator variables were centered at 0.

3) An interaction variable between the intercept and moderator variable was created for each model with a moderator variable, and entered into the model as an independent variable.

4) The variance of the PASAT correct responses outcome variable was reduced by transforming all values into (un-normed) T scores.</td></tr>
<tr><td>B) THE MODEL ESTIMATION DID NOT TERMINATE NORMALLY DUE TO AN ILL-CONDITIONED FISHER INFORMATION MATRIX. CHANGE YOUR MODEL AND/OR STARTING VALUES.
THE MODEL ESTIMATION DID NOT TERMINATE NORMALLY DUE TO A NON-POSITIVE DEFINITE FISHER INFORMATION MATRIX.
THIS MAY BE DUE TO THE STARTING VALUES BUT MAY ALSO BE AN INDICATION OF MODEL NONIDENTIFICATION.
THE CONDITION NUMBER IS ******</td></tr>
</table>

APPENDIX D Study Tables

Author and Year	Number of Participants	Age: mean in years (StDev)	Gender (M/F)	Severity of Injury Variables	GCS	Assessment Measures	Global Outcome Measures	Results
Adoni & McNett 2007	A case study	N/A	N/A	N/A	N/A	N/A	N/A	Pupillary abnormalities can be a symptom of TBI.
Anderson et al. 1993	58 individuals with mild, moderate and severe TBI.	32. Range: 14-84.	53/5	GCS	≤ 8 (N = 29); 9-12 (or8 with no eye opening) (N = 20); 13-15 (N = 9)	None	GOS (given by three separate raters)	High interrater reliability between\ research psychologist and the research worker (*r* of 0.79 *p* =0.001). Interrater reliability was lower betweenresearch psychologist and general practitioner (*r* of 0.49 p = 0.001).
Armstrong disseration 2010	N = 91 severe CHI from 132 patients total	36.5. Mode = 22 Range: </= 21 - > 60	74/17 (M/F)	best day 1 GCS motor score, Marshall CT scan classification of first post-injury scan, best day 1 pupillary response	GCS = 6 (N = 17); GCS = 5 (N = 39) GCS = 4 (N = 10); GCS = 3 (N = 2); GCS = 2 (N = 6); GCS = 1 (N = 15).	NA	GOS-S, GOS-E and DRS	All GOSS scores associated with plausible DRS scores. Strong correlation between scores on the GOSS and the DRS. MODELS: Only age and Best Day 1 GCS motor score consistently made a significant contributions to model prediction.
Audoin et al. 2001	10 primary French-speaking healthy controls	26.6 (6.2) "young;" age data not clear. Means and SD suggest participants could be as young as children and as old as middle aged	72 percent female	N/A- healthy controls	N/A- healthy controls	PASAT: one PASAT trial consisting of 61 single-digit numbers presented at a 3 second ISI, and one control trial comprised of the same series of numbers. Control: to repeat the numbers following each presentation.	N/A-healthy controls	Activation observed in the left dorsolateral prefrontal cortex (assoc. working memory), the left frontopolar cortex (assoc. attention), left parietal lobe, (assoc. working memory, attention and calculation), the left superior temporal gyrus, the left temporal pole and the cingulate gyrus (assoc. working memory), the supplementary motor cortex, the lateral premotor cortex, and the visual associative areas.
Bate, Mathias and Crawford 2001	N = 35 severe non-penetrating TBI and 35 controls	TBI: 28.9 (11.5); C: 30.2 (10.3)	TBI: 28/7 (M/F); C: 20/15 (M/F)	PTA: 43.2 (37.9) days	5.7 (3.1)	Test of Everyday Attention, Stroop Colour Word Test (including Bohnen modified subtest), Symbol Digit Modalities Test, WMS-R Digit Span, Ruff Selective Attention Test, PASAT, National Adult Reading Test-R, PASAT	None	sTBI patients performed worse on Map Search, Telephone Search and Visual Elevator subtests of TEA. Performance of TBI and controls on the established tests were consistent with previous studies. PASAT revealed significant differences between TBI and controls at the two fastest intervals. Repeated Measures ANOVA revealed that increasing rate of presentation was not more detrimental for the TBI group.
Benedict et al. 2006	N = 291 with definite MS; 56 healthy controls	MS: 45.4 (8.9) HC: 43.8 (9.5)	MS: 78 percent female (n = 227). HC: 75 percent female (n = 42).	N/A	N/A	PASAT, COWA, JLO, CVLT-2, BVMT-R, D-KEFS Sorting Test, SDMT. Expanded Disability Status Scale scores were available for 186 patients.	N/A	The number of correct responses on the 3-second block of trials on the PASAT was predictive of current disabled/employment status (odds ratio 3.57, *p* = 0.03), according to the statistical model employing a more conservative definition of disabled/employment status.

Author and Year	Number of Participants	Age: mean in years (StDev)	Gender (M/F)	Severity of Injury Variables	GCS	Assessment Measures	Global Outcome Measures	Results
Biney dissertation 2010	393 individuals with severe TBI	35.44 (13.70). Range 18-91.	332/60	Worst CT Scan: D1/D2: n = 118. D3/D4: n = 74. M1/M2: n = 197. BD1 pupil: Nonreactive: n = 86. Unilateral reactive: n = 26. Bilateral reactive: n = 254.	ER GCS: 6.59 (3.10). Best Day 1 GCS: 7.36 (2.51)	None	DRS. 1 month score: 17.72 (9.43). 3 month score: 14.50 (11.12). 6 month score: 13.79 (12.06).	BAL was not found to be associated with functional outcome in the first six months after TBI when age and injury severity are controlled.
Choi, Ward and Becker 1983	264 individuals with head injury	31	78 percent male.	Oculocephalic responses; 36 percent had bilaterally impaired responses. Other measures were mentioned but not elaborated upon.	Mean admission GCS: 6.6.	None	Dichotomized GOS. 60 percent had good outcome (good recovery or moderate disability).	Results suggested that GCS, oculocephalic response and age can reliably predict dichotomized GOS outcome in severe head injury.
Choi et al. 1998	332 individuals with severe TBI	Trial 1 (n =212): 30.5 ± 13.0 and 32.5 ± 12.6. (stratified by injury severity). Trial 2: 31.9 ± 14.2 and 30.2 ± 11.8.	Not provided.	Not provided.	Admission GCS Range: 3-8.	None	DRS and GOS	They did no find any indication that the DRS was more sensitive than the dichotomized or four-category GOS.
Christodoulou et al. 2001	9 individuals with moderate and severe TBI and 7 healthy controls.	TBI: 32.67 (10.86). HC: 29.71 (7.04). Exclusion criteria included age older than 56.	TBI: 56 percent male. HC: 57 percent male.	n = 6: unspecified GCS. n = 3: presence of anatomical findings on neuroimaging, positive focal neurological signs, or loss of consciousness longer than 30 minutes.	5.71 (2.14). Time collected was not specified. Not available for 3/9 participants.	Modified PASAT: 2 32-second trial blocks. . 2 second ISI. Participants silently added the two most recent numbers, and lift finger at sum of 10. Control: participants imagined brushing their teeth.	None	Individuals with TBI were able to perform the task but made significantly more errors of omission than the healthy controls. Activation patterns were similar for the two groups: similar regions of the frontal, parietal and temporal lobes. In contrast, cerebral activation in the individuals with TBI was more regionally dispersed and more lateralized to the right hemisphere, with lateralization differences most evident in the frontal lobes.
Dikmen et al. 2003	210 individuals with mild to severe TBI	Mean of 36 years old.	82 percent male.	The Head Index of the Abbreviated Injury Scale. Severity rating was based on the length of loss of consciousness, the presence of non-transient neurological deficits, and the presence, location, size and multiplicity of anatomical lesions.	60 percent mild (GCS 13-15), 20 percent moderate (9-12), and 20 percent severe (3-8).	Levin version of the PASAT and the CVLT.	GOS, Center for Epidemiologic Studies Depression Scale, Brief Symptom Inventory, Functional Status Exam, Percentage back to normal, Medical Outcomes Study 36-Item Short-Form Health Survey (SF-36), Modified perceived quality of life, employment and living situation.	They reported a systematic relationship between modified AIS-Head score and performance on the PASAT; participants with more severe AIS-Head ratings performed significantly worse on the PASAT.

Author and Year	Number of Participants	Age: mean in years (StDev)	Gender (M/F)	Severity of Injury Variables	GCS	Assessment Measures	Global Outcome Measures	Results
Ewing-Cobbs et al. 2004	N = 34 mild-mod TBI + 43 severe TBI	Mild-mod: 9.82 (3.22). Severe: 9.38 (3.32). Range-5-15 years old	28 percent Female. 55/22 M/F	duration of coma or impaired consciousness- defined as number of days child could not follow a 1-step command. Duration of impaired consciousness was comparable across age groups.	Average lowest postrecussitation scores: mild-mod TBI: 13.3 (2.12) and severe TBI: 5.7 (2.02). Comparable across age groups within each severity group.	WRAT Reading Recognition, Spelling and Arithmetic subtests. PIAT Reading Comprehension subtest. Child Behavior Checklist	None	Achievement scores increased over time but the rate of increase slowed, representing a deceleration model. Used 3 parameter polynomial function of time to approximate the model, with intercept, slope and curvature as parameters. Time postinjury was centered at 1 year to minimize multicollinearity
Forn et al. 2008	14 primary Spanish-speaking healthy controls	21.9 years (SD: 1.6)	8/6 M/F	N/A- healthy controls	N/A- healthy controls	Modified PASAT: Three 1 -minute blocks. Asked to sum the two most recent numbers and either think about the answer (the covert version) or give it verbally (overt version) Across all blocks, 3 second ISI presentation. Control: participants repeated numbers.	N/A-healthy controls	Across versions activation observed in prefrontal superior gyrus, middle frontal gyrus, and inferior frontal gyrus, superior and inferior parietal regions. Greater activation observed in the left hemisphere across tasks. Overt: greater activation observed in left superior and inferior frontal gyrus, bilateral occipital cortex, caudate nucleus, cerebellum and substantia nigra.
Giacino et al. 1991	28 severely brain-injured patients (not all TBI) who were unable to replicate commands and communicate reliably.	32 years, Range: 16-63.	15/13 M/F	Inability to replicate commands or communicate reliably. Included patients who were comatose or in a vegetative state.	Weekly ratings: Week 1: 9.21 (2.57). Week 2: 9.76 (2.68). Week 3: 10.00 (3.00). Week 4: 10.57 (2.83).	None	DRS: Week 1: 23.36 (2.77). Week 2: 22.63 (2.76). Week 3: 22.54 (3.04). Week 4: 22.04 (2.93).	reported a high correlation between the DRS and the Coma Recovery Scale (CRS), with an r of -.93 (p < 0.01).
Gouvier et al. 1987	40. n = 34 CHI, n = 4 open head injury, n = 2 GSW.	Not provided	27/13 M/F	Not provided.	GCS taken at initial contact in the emergency room, and at admission to the rehabilitation center.	None	The DRS, Levels of Cognitive Functioning Scale, the GOS, the GOS-E and Stover Zeiger ratings.	Found highly correlated DRS observations between 3 raters for 40 participants, with rho values at .98 across the three rater pairs. Also found high test-retest reliability for the DRS, with a rho correlation of .95.
Gronwall & Sampson 1974	40. 10 Mild Concussion (MC), 10 Severe Concussion (SC), 10 Accident/No Concussion (ANC), 10 Normal Control (NC).	MC: 20.1 (2.3). SC: 20.3 (2.7). ANC: 20.1 (1.9). NC: 18.8 (1.9)	40/0 M/F	Duration of PTA and length of hospitalization	None.	PASAT	None	PASAT performance of recently concussed individuals was significantly worse than both accident and normal controls. Accident and normal controls performed similarly.
Gronwall & Wrightson 1981	71	Range: 17-30	Not provided.	PTA determined by retrospective questioning	Not provided.	I: WMS, PASAT, Quick-test. II: PASAT, Selective Reminding Task, Visual Sequential Memory subtest	None	I: PASAT loaded onto Factor 1, which seems to be concerned with attention, concentration and information processing capacity. PTA did not load highly on any one factor.
Hall, Cope & Rappaport 1985	70	27. Range 15-60	Not provided.	Length of coma (average: 32 days)	Not provided.	None	GOS and DRS	Significant correlations between GOS and DRS. DRS produced wider distribution of scores, provided more specific information, and was more sensitive to change over time.

Author and Year	Number of Participants	Age: mean in years (StDev)	Gender (M/F)	Severity of Injury Variables	GCS	Assessment Measures	Global Outcome Measures	Results
Hall et al. 1993	332	34.5 (16.0)	78 percent male.	Length of coma, length of PTA, Revised Trauma Score, and CT pathology	8.2 (3.7)	Levels of Cognitive Functioning Scale	DRS, Functional Independence Measure, and Functional Assessment Measure	High significant correlationswere reported between the DRS, the Functional Independence Measure and the Functional Assessment Measure.
Hattori et al. 2009	15 with mild TBI and 15 healthy controls	TBI: 45 (11). Range: 27-60. HC: 43 (9). Range: 28-58.	TBI: 3/12. HC: 3/12 (M/F)	Loss of consciousness < 30 min, PTA < 24 hours. Criteria from the Head Injury Interdisciplinary Special Interest Group of the ACRM	Not provided.	PASAT	None	Healthy controls showed bilateral activation in superior temporal cortex, precentral gyrus, cerebellum, and left precentral gyrus. mild TBI showed larger areas of supratentorial activation but smaller areas of cerebellar activation, suggesting frontocerebellar dissociation.
Higginson, Arnett and Voss 2000	31 participants with definite or probable multiple sclerosis	46.7 (7.6)	Not provided.	N/A	N/A	PASAT, CVLT, The 7/24 Spatial Recall Test, Symbol Digit Modalities Test, RBMT, TEA, Memory Rating Scale, BDI, Fatigue Impact Scale, EDSS, Environmental Status Scale (filled out by participants and SOs)	None	PASAT performance across both trials was found to correlate significantly with the Environmental Status Scale scores (R = -.30 p<0.05). PASAT performance was not a significant predictor of Environmental Status Scale Scores in a stepwise regression analysis comparing tests of attention.
Hiscock, Caroselli & Kimball 1998	48	23.4 (5.3)	24/24	N/A-healthy controls	N/A-healthy controls	PASAT and Visual Addition Task (VAT)	N/A- healthy controls	Individuals tended to perform better on a visual analogue of the PASAT. Individuals also performed better when giving written responses instead of oral ones, though only during trials with standard PASAT ISIs.
Kay et al. 1995	164	For N = 131. 32 (13) Range: 11-67.	For N = 158. 60 percent Male, 40 percent female.	Duration of coma and loss of consciousness	None	The New York University Head Injury Family Interview (NYU-HIFI)	None	Factor analysis on the items in the Problem Checklist of the NYU-HIFI produced three factors: an affective/behavioral factor, a cognitive factor, and a physical/dependency factor. This study is a good reference for the PCL and the NYU-HIFI in general.
King 1996	50 head-injured adults of varying severity	33 (12.7). Range: 17-65.	23/27 M/F	length of PTA (hours)	None	PASAT, Stroop, Hospital Anxiety and Depression Scale (HADS) Anxiety and Depression scores, the Short Orientation and Memory Concentration Test (SOMC), the IES Intrusions and Avoidance scores, the Adult Memory and Information Processing Battery (AMIPB), and RPQ (PCS severity)	None	Combination of scores gave a multiple correlation coefficient of R = 0.86, accounting for 74 percent of the variance in scores on a PCS rating scale. The scores included PASAT (2.4, 1.6 and 1.2 ISI trial blocks), Stroop speeded word reading subtest, HADS, length of PTA (hours), the SOMC, and AMIPB Information Processing subtest

Author and Year	Number of Participants	Age: mean in years (StDev)	Gender (M/F)	Severity of Injury Variables	GCS	Assessment Measures	Global Outcome Measures	Results
Larrabee & Curtiss 1995	112 total. 35 with closed head trauma. Multiple other etiologies also evaluated	39.34 (13.19) Range: 16-70	56/56 M/F	N/A for this study	N/A for this study	Expanded Paired Associates Test, the Verbal Selective Reminding Test, the Continuous Recognition Memory Test, the Continuous Visual Memory Test, the PASAT, the WMS Mental Control and Visual Reproduction, the WAIS-R Digit Span, Trail Making Test A and B and Serial Digit Learning. Information, Vocabulary, Block Design and Object Assembly; WMS-R Mental Control	None	In both immediate and delayed recall FAs, PASAT loaded onto a factor with Digit Span, Serial Digits, and Mental Control. This factor defines a dimension of attention/immediate memory and information processing accounting for 11% and 11.3% of the variance respectively. Supports the construct validity of the PASAT as a measure of attention/immediate memory and information processing.
Levin et al. 1987	57 TBI (From 155 head injured patients and 56 healthy controls.)	Site 1: 21.9 (5.7). Site 2: 22 (4.2). Site 3: 23.9 (6.3).	35/22	Loss of consciousness < 20 min, no focal neurological deficit, no intracranial mass lesion,	GCS 13-15. Site 1: 14.8 (0.4). Site 2: 15 (0.2). Site 3: 14.6 (1.1).	PASAT, digit span, learning and memory of 20 animal names, visual learning and memory of geometric designs, and digit symbol subtest.	None	Pervasive impairments across neuropsychological measures was observed. This study presented the Levin version of PASAT administration.
Levin et al. 1990	300	27 (10)	76 percent /24 percent M/F	First CT scan, duration of impaired consciousness, ICP and pupillary reactivity score	Lowest postresuscitation GCS	Verbal Memory, PASAT, Trail Making Test, Modified Card Sorting, Visu al Naming, Visual Memory, Block Design and Grooved Pegboard.	GOS	Lowest postresuscitation GCS and pupillary reactivity score were predictive of 1 years GOS score and neuropsychological performance.
Levin et al. 2001a	mild (n = 30) to moderate (n = 13) traumatic brain injury (TBI) or general trauma (n = 44).	TBI: 34.3 (14.1) General trauma: 36.9 (13.7)	TBI: 13 F/30 M. General trauma: 16 F/28 M	Positive CT findings for TBI: 29 negative/12 positive. Injury Severity Score TBI: 6.00 (0–26); general trauma: 3.63 (0–17). Also gave the Abbreviated Injury Scale.	GCS (median = 15), TBI: 14.41 (9–15). General trauma: 15.	Grooved Pegboard Test, Selective Reminding Test, Rey Complex Figure Test, PASAT, Symbol Digit Modalities Test, Wisconsin Card Sorting Test, Social Support Questionnaire, Community Integration Questionnaire, Visual Analogue Scale for Depression, Center for Epidemiological Studies-Depression Scale, PTSD Checklist- Civilian version.	GOS and GOS-E	GOS-E had a significantly better fit for the Community Integration Questionnaire ($R2 = 0.35$ vs 0.26, $p < 0.01$), trial 1 of the Paced Auditory Serial Addition Test ($R2 = 0.37$ vs 0.19, $p \leq 0.01$), and right hand Grooved Pegboard ($R2 = 0.21$ vs 0.09, $p = 0.06$ vs 0.08). GOS had a better fit for Satisfaction score of the Social Support Questionnaire (GOS $R2 = 0.10$, $p = 0.05$ vs GOS-E $R2 = 0.12$, $p = 0.23$). Results suggested that the GOS-E is more sensitive to change than the GOS between 3 months and 6 months post-injury.
Levin et al. 2001b	122 (78 severe, 44 mild) longitudinal.	mean age at 3 month eval: 9.95 years (3.04). range: 5-15 years. See article for mean ages at each evaluation. Average age at injury was 9.6 years	52% boys, 48% girls (Mild CHI); 58% boys, 42% girls (Severe CHI)	Severe CHI = GCS =/< 8. Mild CHI = GCS of 13-15 and normal CT at initial hospitalization and normal MRI by 3 months post-injury.	Mild: 14.6 (0.6). Severe: 5.7 (1.8) . Unclear which GCS was recorded.	PPVT-R, CVLT-C, and COWA- Child asked to generate as many words as possible beginning with a designated letter within 60 s, repeated for 3 letters. Completed on at least 3 occasions	None	An interaction of age, followup interval, and CHI severity was revealed. WF recovery was slower after severe CHI in younger children, compared to severe CHI in older children or mild CHI in younger children. Model with random intercept and random slope fitted best. Receptive vocabulary increased more rapidly after injury in young children. GCA of CVLT-C scores demonstrated greater improvement in verbal recall over timein younger children compared to older children. A decrease over time between word list recall scores for mild and severe CHI children was also evident.

Author and Year	Number of Participants	Age: mean in years (StDev)	Gender (M/F)	Severity of Injury Variables	GCS	Assessment Measures	Global Outcome Measures	Results
Maas et al. 2007	Individual patient data from the IMPACT database: CT classification N = 5209. basal cisterns N = 3861. shift N = 4698. tSAH N = 7407. Intracranial lesions N = 7613.	Not provided	Not provided.	Marshall CT classification, status of basal cistern, and the presence of midline shift, traumatic subarachnoid hemorrhage (tSAH), and intracranial lesions.	None	None	GOS (N = 8721)	CT classification and individual characteristics were strongly associated with 6 month outcome. Intracranial abnormalities (CT DII-ML) were observed in 93 percent of 5209 patients. Compressed/absent basal cisterns in 12 percent of D1 or DII patients. Normal cisterns observed in 35 percent of DIII patients. DIII and DIV were most related to mortality. Prognostic effect of midline shift was linear. tSAH had strong prognostic effect.
Marmarou et al. 2007	3728 with moderate and severe injuries from IMPACT database.	Not provided	Not provided.	Pupillary Response	Full pre-hospital GCS was available for 68 percent of patients. First in-hospital scores were available for 78 percent. (In table organized by study)	None	GOS	Observed considerable variability in GCS motor score and pupillary reactivity across time points, from injury to postresuscitation assessment. Greater improvement over time was observed for patients with lower GCS motor scores and compromised pupillary reactivity. Patients with high GCS motor scores and reactive pupils showed more of a range for deterioration.
Marshall et al. 1991	746 patients with severe head injury.	153 patients were less than or equal to 40 years old. 24 patients were over 40. More specific data not provide.	Not provided.	Marshall CT classification, ICP and postresuscitation pupil reactivity.	Severe: defined as GCS score of 8 or less after nonsurgical resuscitation.	None	GOS	CT classification was a highly significant predictor of mortality with age and GCS motor score in the model.
McCauley, Hannay and Swank 2001	SO report group (SO): N = 55. No SO report group (NoSO): N = 83	SO: 32.0 (13.6) NoSO: 31.38 (10.03) Range: 15-55.	SO: 46/9. NoSO: 67/16	Best Day 1 GCS and CT abnormalities.	**Best Day 1 GCS: SO**: 10.04 (3.34) **NoSO:** 9.80 (3.54). Complicated-Mild (12-15) SO: N = 16, NoSO N = 22. Moderate (9-12) SO: N = 15, NoSO: N = 16. Severe (3-8). SO: N = 24, NoSO: N = 45.	The New York University Head Injury Family Interview (NYU-HIFI)	DRS	Found linear and curvilinear recovery curve components were significantly related to SO-perceived severity of neurobehavioral impairments and severity and burden of cognitive deficits. Only SO-perceived severity and burden of physical impairments was associated with the intercept of the DRS recovery curve.
Neese et al. 2000	75 (89 percent severe TBI)	28.84 (9.13).	73 percent male	PTA > 7 days, or length of time > 1 day before ability to follow a command.	emergency room GCS of 8 or lower (for severe TBI)	WAIS-R, TONI-2, WRAT-3 (Reading, Spelling, Arithmetic), PIAT-R, COWA, MAE Token Test, Naming task, Sentence Repetition, Facial Recognition, JOLO, Visual Form Discrimination, WCST, CVLT, WMS-R (Logical Memory &Visual Reproduction)	DRS	Better levels of functioning (lower DRS scores) were associated significantly with better performance across the cognitive domains.

Author and Year	Number of Participants	Age: mean in years (StDev)	Gender (M/F)	Severity of Injury Variables	GCS	Assessment Measures	Global Outcome Measures	Results
O'Donnell et al. 1994	117 adults, mixed etiology.	30.2 (10.5) Range: 18-61	79/38 M/F	at least 2 hours of PTA and a minimal medical diagnosis of concussion (n = 22)	None	WAIS-R. Halstead-Reitan, Category Test, WCST, PASAT, VSAT, and Trail Making Test.	None	The PASAT, the VSAT and TMT-B loaded onto factor 1, which is thought to be an attention factor. CT and WCST loaded onto factor 2 which is thought to be a conceptual factor.
Pastorek, Hannay and Contant 2004	105 head injury patients	31.5 (12.7) Range: 15-72	92/13 (M/F)	Pupillary Response	**Best Day 1 GCS**: Mean: 10.3, StDev: 3.4, Range: 3-15	Test of Complex Ideational Material from the BDAE; the Mini Token Test; Auditory Number Search Test; and Visual Number Search Test, all given at 1 month post-injury	**DRS (6mo):** Mean: 2.97. StDev: 4.20, Range: 0-30. **GOS (6 mo):** GR: 48, MD: 43, SD: 13, D: 1.	Raw scores on the modified CIM accounted for a significant portion of variance in DRS scores (4.4) above what is accounted for by age, education, Best Day 1 GCS and pupillary response. Testability (based on test completion codes) on all four tests at 1 month post injury accounted for a larger portion of the variance in DRS scores (10.1–13.2%) and improved prediction of GOS scores.
Pettigrew, Wilson & Teasdale 1998	80 head-injured patients	42.3 (19.3) Range: 16-89	64/16 (M/F)	Worst recorded GCS	29% GCS < 8 (severe), 14% GCS 9-12 (moderate), 57% GCS 13-15 (mild).	None	GOS, DRS, Barthel ADL Index	Significant correlation between GOS and Barthel ADL index ratings (Spearman p 0.61, p , 0.001). Stronger relationship between DRS and GOS (Spearman p -0.89, p < 0.001).
Ponsford & Kinsella 1992	47 individuals with severe closed-head injury and 30 injury controls.	23.4 (7.4). Range: 16-43.	29/18	at least 7 days of PTA, presence of CT scan abnormalities.	Admission GCS (for 38/47 patients) fell between 3-9	PASAT, Stroop, Symbol Digit Modalities Test, Cancellation, and simple and choice reaction-time tests	None	the only significant differences in error scores between head-injured and control groups was observed during PASAT performance; head-injured individuals performed significantly worse than controls across all PASAT trials.
Rappaport et al 1982	88	Not provided	Not provided.	abnormality ratings of visual, auditory and somatosensory brain evoked potentials	None	None	DRS with pairs of 3 raters. And GOS	Reported correlations fell between .97 and .98, and were highly significant (*p* < 0.01). Correlations between DRS scores and independent measures of the participants' CNS functioning were significant (r = 0.35-.78).
Satz et al. 1998	TBI: 100 individuals. Other Injury Controls: 30.	TBI: 32.1 (14.0), Range: 16-77. Controls: 34.0 (12.7), Range: 17-70.	TBI: 83% Male. Controls: 73% Male.	Initial GCS and CT scans from admission to ER; Abbreviated Injury Severity Score.	Initial GCS from admission to ER. Mean: 9.6, StDev: 4.2, Range: 3-15	Grooved Pegboard, SDMT, Color Trails 1 & 2, RAVLT, Word List Memory Test, AIMS, Auditory Reaction Time, Span of Apprehension, Digit Span Distractibility Test, Symptom Checklist-90, Neurobehavioural Rating Scale Item #13, Neuropsychology Behavioural and Affect Profile, Patient Competency Rating Scale, Employability Rating Scale	GOS	The strongest associations occurred between the GOS category and performance on neuropsychological measures across four domains: motor (F = 12.0-13.2, *p* = 0.001), psychomotor (F = 3.4-8.0, *p* = 0.02-0.001), memory (F = 2.26 – 6.03, *p* = 0.050-0.001) and attention (F = 2.7-2.9, *p* = 0.050-0.035).
Scranton, Fogel & Erdman 1970	186	Provided, broken down by 10 disability groups	Not provided.	Disability groups defined by ratings on 27 physical and psychosocial variables.	None	None	None	Improvement in physical function was observed across patients at admission, discharge and followup. Residual degree of dependence was observed for most patients at follow-up.

Author and Year	Number of Participants	Age: mean in years (StDev)	Gender (M/F)	Severity of Injury Variables	GCS	Assessment Measures	Global Outcome Measures	Results
Servadei et al. 2000	206	Provided, broken down by outcome and 6 age ranges.	144/62	Worst CT scan parameters from serial CT scans. All participants had acute subdural hematoma of 5 mm or more. Pupillary abnormalities.	Admission GCS: Range: 3-15	None	6 mo GOS: 78 patients showed good recovery. 18 patients showed moderate disability. 12 had severe disability. 4 in persistent vegetative state, 94 died.	Most powerful predictor of worse outcomes was presence of SAH alone or associated with brain contusions on 'worst' CT scan (Odds ratio 0.37, p < 0.004). Hematoma thickness, midline shift and basal cistern status also correlated with outcome.
Sherman, Strauss & Spellacy 1997	N = 441	32.7 (12.4)	283/158 (M/F)	CT/MRI abnormalities, PTA and LOC	None	PASAT (Wilson version), WAIS-R Arithmetic, Digit Symbol and Digit Span, Sentence Repetition, Trigrams, Corsi Blocks, Cancellation Test, Visual and Auditory Reaction Time, Trail Making Test, Stroop and WCST	None	PASAT performance correlated with several measures of attention. A substantial amount of the variance in PASAT scores was accounted for by tests measuring mathematical knowledge. PASAT performance also correlated moderately with other tests measuring conceptually unrelated abilities, including verbal ability, verbal memory, academic achievement, and complex motor skills.
Stover & Zeiger 1976	48	Range: 2-19.	36/12	Coma Duration longer than 7 days.	None	None	Stover-Zeiger Rating Scale	Duration of coma is not a clear predictor of functional outcome. Study describes the Stover-Zeiger Rating Scale.
Struchen, Hannay, Contant & Robertson 2001	184 patients	34.01 (15.75). Range: 14-84	83 percent M/17 percent F.	Continuous monitoring of intracranial pressure, mean arterial pressure, jugular venous oxygen saturation and cerebral perfusion pressure. Mean Injury Severity Score: 26.61 (5.84).	Mean emergency room GCS: 6.91 (3.19)	None	GOS, DRS	GOS and DRS scores related to longer durations of adverse physiological events across time points. When analyses excluded patients who died, adverse physiological events related to DRS scores only. Results suggest DRS more sensitive to changes in level of functioning and might be better suited to measuring longitudinal recovery.
Tombaugh et al. 2006	Control: N = 40. miTBI: N = 40, sTBI: N = 38	Control. A: 36.9 years (13.2) V: 24.5 years (5.9) miTBI. A: 33.8 years (15.0) V: 49.0 years (18.8) sTBI. A: years 41.5 (14.1) V: 31.7 years (13.5)	Control. A: 9/11 V: 11/9 miTBI. A: 14/6 V: 15/5 sTBI. A: 12/8 V: 11/7 (M/F)	GCS and LOC	miTBI = GCS >13 sTBI: GCS < 13 (n = 17: mean 7.71, SD 3.75). **Time of GCS unknown**.	16 miTBI administered 21 Word Test. sTBI administered the TOMM. Both groups: A and V Adjusting-PSAT ISI Threshold scores	None	Performance (threshold values) progressively declined as a function of the severity of TBI with the visual Adjusting-PSAT, with visual producing consistently lower thresholds than auditory.

Author and Year	Number of Participants	Age: mean in years (StDev)	Gender (M/F)	Severity of Injury Variables	GCS	Assessment Measures	Global Outcome Measures	Results
Tudos et al. 2014	20	23.0 years (2.7)	10/10	N/A- healthy controls	N/A- healthy controls	PASAT and Paced Verbal Serial Addition Test (PVSAT): four 6-minute runs. PASAT for two of the runs. (eyes were closed). PVSAT, for other two runs. Each run was six 30-second blocks. Asked to raise thumb when the two most recent numbers summed to 10. Blocks alternated with six 30-second control blocks. Participant raised thumb when 10 was presented. All 3-second ISI.	N/A	Common activation pattern: bilateral supplementary motor area, insular cortex, right caudate, left inferior frontal gyrus, bilateral inferior frontal junction, right middle frontal gyrus, bilateral intraparietal sulcus, vermis, and bilateral cerebellum. Modality-dependent areas of activation: PASAT: greater activation in right frontal eye field, right lingual and fusiform gyrus, left lingual gyrus, right intracalcarine cortex, and left occipital pole. PVSAT: greater in bilateral LO1 lateral occipital complex, left LO2 lateral occipital complex, and fusiform gyrus.
Veramonti 2005	114 individuals with TBI and their Significant Others.	29.6 years (12.5)	95/19 (M/F)	Best Day 1 pupillary reactivity: 0 blown (n = 86), 1 blown (n = 5), 2 blown (n = 12), unknown (n = 11). CT findings: DI (n = 3), DII (n = 57), DIII (n = 15), DIV (n = 4), EML (n = 27), N-EML (n = 0).	Best Day 1 GCS: 3-8 (n = 47), 9-12 (n = 36), 13-15 (n = 31).	HI-FI Problem Checklist	DRS: DRS = 0 (n = 19), DRS = 1 (n = 9), DRS = 2-3 (n = 24), DRS = 4-6 (n = 38), DRS = 7-11 (n = 17), DRS = 12-16 (n = 6), DRS = 17-21 (n = 1), DRS = 22-30 (n = 0)	Factor analysis of the problem checklist revealed a four-factor solution accounting for 48 percent of the variance, across a set of 41 items. On average, participants with more severe TBI rated problems as less severe than their SO.
Wilson, Pettigrew and Teasdale 1998	50	39.4 (16.5). Range: 18-76.	42/8	GCS	Worst recorded GCS. 30 percent GCS 3-8; 14 percent GCS 9-12; 56 percent GCS 13-15.	None	GOS-S and GOS-ES. Reviewers were research psychologist and research nurse.	Found high interrater reliability for the structured interviews of the GOS and GOS-E, with weighted kappa values of 0.89 and 0.85 respectively.

APPENDIX E Assessment Forms

Form 1. Glasgow Coma Scale (GCS) Table.

Glasgow Coma Scale (GCS) Acute Assessment
Eye Opening
4 Opens eyes Spontaneously 3 Opens eyes on command 2 Opens eyes to painful stimuli 1 No eye response
Verbal Response
5 Oriented conversation 4 Confused speech 3 Inappropriate words 2 Incomprehensible sounds (e.g., groans) 1 None
Motor response
6 Obeys simple commands 5 Localizes to pain 4 Normal Flexion/Withdraw to pain 3 Abnormal flexion to pain 2 Extension to pain 1 None

Form 2. Item Differences on the Disability Rating Scale.

ITEM DEFINITIONS for DRS (Disability Rating Scale)

Eye opening

0— SPONTANEOUS: eyes open with sleep/wake rhythms indicating active and arousal mechanisms; does not assume awareness.
1— TO SPEECH AND/OR SENSORY STIMULATION: a response to any verbal approach, whether spoken or shouted, not necessarily the command to open the eyes. Also, response to touch, mild pressure.
2— TO PAIN: tested by a painful stimulus.(Standard painful stimulus is the application of pressure across index fingernail of best side with wood or a pencil; for quadriplegics pinch nose tip and rate as 0, 1, 2 or 5.)
3— NONE: no eye opening even to painful stimulation.

Best communication ability (if patient cannot use voice because of tracheostomy or is aphasic or dysarthric or has vocal cord paralysis or voice dysfunction then estimate patient's best response and enter note under comments.)

0— ORIENTED: implies awareness of self and the environment. Patient able to tell you a) who he is; b) where he is; c) why he is there; d) year; e) season; f) month; g) day; h) time of day.
1— CONFUSED: attention can be held and patient responds to questions but responses are delayed and/or indicate varying degrees of disorientation and confusion.
2— INAPPROPRIATE: intelligible articulation but speech is used only in an exclamatory or random way (such as shouting and swearing); no sustained communication exchange is possible.
3— INCOMPREHENSIBLE: moaning, groaning or sounds without recognizable words; no consistent communication signs.
4— NONE: no sounds or communication signs from patient.

Best motor response

0— OBEYING: obeying command to move finger on best side. If no response or not suitable try another command such as "move lips," "blink eyes," etc. Do not include grasp or other reflex responses.
1— LOCALIZING: a painful stimulus[1] at more than one site causes a limb to move (even slightly) in an attempt to remove it. It is a deliberate motor act to move away from or remove the source of noxious stimulation. If there is doubt as to whether withdrawal or localization has occurred after 3 or 4 painful stimulations, rate as localization.
2— WITHDRAWING: any generalized movement away from a noxious stimulus that is more than a simple reflex response.
3— FLEXING: painful stimulation results in either flexion at the elbow, rapid withdrawal with abduction of the shoulder or a slow withdrawal with adduction of the shoulder. If there is confusion between flexing and withdrawing, then use pin prick on hands, then face.
4— EXTENDING: painful stimulation results in extension of the limb.
5— NONE: no response can be elicited. Usually associated with hypotonia. Exclude spinal transection as an explanation of lack of response; be satisfied that an adequate stimulus has been applied.

Cognitive ability for feeding, toileting and grooming.

Rate each of the three functions separately. For each function answer the question, does the patient show awareness of how and when to perform each specified activity. *Ignore motor disabilities that interfere with carrying out a function, this is rated under Level of Functioning described below.* Rate best response for toileting based on bowel and bladder behavior. Grooming refers to bathing, washing, brushing of teeth, shaving, combing or brushing of hair and dressing.

0— COMPLETE: *continuously shows awareness that he knows how* to feed, toilet or groom self and can convey unambiguous information that he *knows when* this activity should occur.
1— PARTIAL: *intermittently shows awareness that he knows how* to feed, toilet or groom self and/or can intermittently convey reasonably clearly information he *knows when* the activity should occur.
2— MINIMAL: *shows questionable or infrequent awareness that he knows in a primitive way how* to feed, toilet or groom self and/or shows infrequently by certain signs, sounds or activities that he is *vaguely aware* when the activity should occur.
3— NONE: *shows virtually no awareness at any time that he knows how* to feed, toilet or groom self and *cannot convey information by signs, sounds, or activity that he knows when* the activity should occur.

Level of functioning

0— COMPLETELY INDEPENDENT: able to live as he wishes, requiring no restriction due to physical, mental, emotional or social problems.
1— INDEPENDENT IN SPECIAL ENVIRONMENT: capable of functioning independently when needed requirements are met (mechanical aids).
2— MILDLY DEPENDENT: able to care for most of own needs but requires limited assistance due to physical, cognitive and/or emotional problems (e.g. needs non-resident helper).
3— MODERATELY DEPENDENT: able to care for self partially but needs another person at all times.
4— MARKEDLY DEPENDENT: needs help with all major activities and the assistance of another person at all times.
5— TOTALLY DEPENDENT: not able to assist in own care and requires 24-hour nursing care.

"Employability"

The psychosocial adaptability or "employability" item takes into account overall cognitive and physical ability to be an employee, homemaker or student. This determination should take into account considerations such as the following:

1. Able to understand, remember and follow instructions; 2. Can plan and carry out tasks at least at the level of an office clerk or in simple routine, repetitive industrial situations or can do school assignments; 3. Ability to remain oriented, relevant and appropriate in work and other psychosocial situations; 4. Ability to get to and from work or shopping centers using private or public transportation effectively; 5. Ability to deal with number concepts; 6. Ability to make purchases and handle simple money exchange problems; 7. Ability to keep track of time schedules and appointments.

0— NOT RESTRICTED: can compete in the open market for a relatively wide range of jobs commensurate with existing skills; or can initiate, plan, execute and assume responsibilities associated with homemaking; or can understand and carry out most age relevant school assignments.
1— SELECTED JOBS, COMPETITIVE: can compete in a limited job market for a relatively narrow range of jobs because of limitations of the type described above and/or because of some physical limitations; or can initiate, plan, execute and assume many but not all responsibilities associated with homemaking; or can understand and carry out many but not all school assignments.
2— SHELTERED WORKSHOP, NON-COMPETITIVE: cannot compete successfully in job market because of limitations described above and/or because of moderate or severe physical limitations; or cannot without major assistance initiate, plan, execute and assume responsibilities for homemaking; or cannot understand and carry out even relatively simple school assignments without assistance.
3— NOT EMPLOYABLE: completely unemployable because of extreme psychosocial limitations of the type described above; or completely unable to initiate, plan, execute and assume any responsibilities associated with homemaking; or cannot understand or carry out any school assignments.

Instructions: Place date of rating at top of column. Place appropriate rating next to each of the eight items listed. Add eight ratings to obtain total DRS score

---

[1]*Standard painful stimulus is the application of pressure across fingernail of best side with wood of a pencil; for quadriplegics nose tip and rate as 0, 1, 2 or 5.*

Form 3. Comparison of the Items on the DRS and GCS.

DISABILITY RATING SCALE VS. GLASGOW COMA SCALE

EYE OPENING*

GCS	Response	DRS
4	Spontaneously	0
3	To verbal stimuli	1
2	To painful stimuli	2
1	None	3

* If the patient has ecchymosis (bruising around an eye) around both eyes, you may still be able to see some spontaneous eye opening. For instance one eye or both may be open a little bit spontaneously and may be completely closed when the patient is sleeping.

VERBAL RESPONSE (GCS) OR COMMUNICATION ABILITY (DRS) **

GCS	Response	DRS
5	Oriented	0
4	Confused	1
3	Inappropriate words	2
2	Incomprehensible sounds	3
1	None	4

**

1. Note if patient is trached (TR) or intubated (ET)

2. If patient is TR or ET and can't make verbal responses, use 1 for GCS calculation but do not necessarily use 4 for the DRS .

3. If patient is TR or ET, use all other methods of communication to determine the score for communication ability for DRS calculation and put in DRS section. (See detailed instructions for the DRS.)

MOTOR RESPONSE

GCS	Response	DRS
6	Obeys commands	0
5	Localizes to pain	1
4	Withdraws to pain	2
3	Abnormal flexion	3
2	Abnormal extension	4
1	None	5

UH-NR 11/18/2006

Form 4. Traditional GOS Outcome Categories.

Glascow Outcome Scale

5 **Death**
(a) as a direct result of brain trauma
(b) patient regained consciousness, died thereafter from secondary Complications or other causes

4 **Vegetative State**
Patient remains unresponsive and speechless for an extended period of time. He may open his eyes and show sleep/wake cycles but show an absence of function in the cerebral cortex as judged behaviorally

3 **Severe disability; conscious but disabled**
Dependent for daily support by reason of mental or physical disability, usually a combination of both. Severe mental disability may occasionally justify this classification in a patient with little or no physical disability.

2 **Moderate disability; disabled but independent**
Can travel by public transport and work in a sheltered environment and can therefore be independent insofar as daily life is concerned. The disabilities include varying degrees of dysphasia, hemiparesis, or ataxia, as well as intellectual and memory deficits and personality change. Independence is greater than simple ability to maintain self-care within the patient's home.

1 **Good recovery**
Resumption of normal life even though there may be minor neurologic and pathologic deficits.

Jennett and Bond (1975)
Jennett et. al. (1981)
Maas et. al. (1983)

Form 5. Structured Interview for the GOS (GOS-S).

STRUCTURED INTERVIEW FOR THE GOS (GOS-S)

Glasgow Outcome Scale

Patient HI# __________ Study # ________ Date of interview:___________ Scoring Check:
Initial 1: ____
Date of Birth:__________ Date of injury___________ Gender: M / F Initial 2: ____

Age at injury:__________ Interval post-injury:____________

Respondent: Patient alone Relative/friend/ carer alone Patient + relative/friend/carer

Interviewer:_______________________________

CIRCLE CORRECT ANSWER TO EACH QUESTION
Answers: Yes, No, and Unknown (Uk)

CONSCIOUSNESS

1. Anyone who shows ability to obey even simple commands, or utter any word or communicate specifically in any other way is no longer considered to be in the vegetative state. Eye movements are not reliable evidence of meaningful responsiveness. Corroborate with nursing staff. Confirmation of VS requires full assessment as in the Royal College of Physician Guidelines.

Is the head injured person able to obey simple commands, or say any words, or communicate specifically in any other way?	No (1) (VS)	Yes (2)	Uk (9)

INDEPENDENCE IN THE HOME

2a. For a "No" answer to the following question about needing assistance, patients should be able to look after themselves at home for 24 hours if necessary, though they need not actually look after themselves. Independence includes the ability to plan for and carry out the following activities: getting washed, putting on clean clothes without prompting, preparing food for themselves, dealing with callers, and handling minor domestic crises. The person should be able to carry out activities without needing prompting or reminding, and should be capable of being left alone overnight.

Is the assistance of another person at home essential every day for some activities of daily living?	No (1)	Yes (2) (SD)	Uk (9)
2c. Was assistance at home essential before the injury?	No (1)	Yes (2)	Uk (9)

INDEPENDENCE OUTSIDE THE HOME

3a. For a "Yes" answer to the following question about being able to shop without assistance, patients should be able to plan what to buy, take care of money themselves, and behave appropriately in public. They need not normally shop, but must be able to do so.

Are they able to shop without assistance?	No (1) (SD)	Yes (2)	Uk (9)
3b. Were they able to shop without assistance before the injury?	No (1)	Yes (2)	Uk (9)

4a. For "Yes" answer to the following question about patients being able to travel without assistance, patients may drive or use public transport to get around. Ability to use a taxi is sufficient, provided the person can phone for it themselves and instruct the driver.

Are they able to travel locally without assistance?	No (1) (SD)	Yes (2)	Uk (9)
4b. Were they able to travel without assistance before the injury?	No (1)	Yes (2)	Uk (9)

IRB NUMBER: HSC-MS-07-0008
IRB APPROVAL DATE: 6/15/2007

Form 6. PASAT Instructions.

Verbal Instructions Given to the Patient: "I am going to ask you to listen to a recording. On this tape, you will hear some numbers. The numbers will only be from 1 to 9. You will hear a number followed by a short pause, another number, a short pause, and so on. Please add the first number and the second number and then say out loud the total. When you hear the third number, add it only to the second number and tell me the total. Remember, add each number to the immediately preceding number. Let's do some examples for practice." Present the following series of numbers slowly and correct any errors made by the patient. Training should continue until the patient gives at least 3 correct responses in at least 1 practice series. The examiner can create additional series as needed. The examiner may also write-out the practice series to explain it to the subject if necessary. Subjects should be reminded not to keep running total. If a subject is unable to provide a correct response to any of the trials in the practice series, discontinue this test.

Practice Series A		Practice Series B		Practice Series C		Practice Series D	
1- - - - -	Response	3- - - - -	Response	6- - - - -	Response	4- - - - -	Response
2- - - - -	3	5- - - - -	8	3- - - - -	9	9- - - - -	13
3- - - - -	5	4- - - - -	9	7- - - - -	10	5- - - - -	14
4- - - - -	7	2- - - - -	6	1- - - - -	8	2- - - - -	7

Additional Verbal Instructions: "Very good. We will now begin the tape recorded series. Please say your answers quickly and indicate your answer before the next number is presented. If you lose your place and stop, try to resume your addition as soon as possible. Everyone finds that they have trouble keeping up as the numbers get faster. Just do your best." (Begin Test)

Form 7. PASAT Response Form, Levin Version

Paced Auditory Serial Addition Task

Name: ______________________ HI#: ________ Date: __________

Medical Record #: ______________________

Series 1	Series 2	Series 3	Series 4
9 --	2 --	4 --	3 --
1 10 ____	4 6 ____	8 12 ____	2 5 ____
4 5 ____	5 9 ____	6 14 ____	6 8 ____
2 6 ____	4 9 ____	2 8 ____	5 11 ____
8 10 ____	3 7 ____	2 4 ____	4 9 ____
6 14 ____	1 4 ____	9 11 ____	3 7 ____
5 11 ____	8 9 ____	3 12 ____	1 4 ____
3 8 ____	6 14 ____	4 7 ____	6 7 ____
4 7 ____	9 15 ____	5 9 ____	5 11 ____
9 13 ____	2 11 ____	8 13 ____	9 14 ____
1 10 ____	9 11 ____	1 9 ____	8 17 ____
3 4 ____	8 17 ____	6 7 ____	4 12 ____
6 9 ____	6 14 ____	3 9 ____	2 6 ____
8 14 ____	1 7 ____	8 11 ____	1 3 ____
2 10 ____	3 4 ____	6 14 ____	2 3 ____
5 7 ____	4 7 ____	2 8 ____	4 6 ____
1 6 ____	5 9 ____	4 6 ____	9 13 ____
8 9 ____	2 7 ____	1 5 ____	3 12 ____
6 14 ____	1 3 ____	9 10 ____	6 9 ____
9 15 ____	9 10 ____	5 14 ____	8 14 ____
2 11 ____	4 13 ____	1 6 ____	5 13 ____
4 6 ____	5 9 ____	9 10 ____	4 9 ____
3 7 ____	6 11 ____	8 17 ____	3 7 ____
5 8 ____	2 8 ____	2 10 ____	8 11 ____
6 11 ____	3 5 ____	5 7 ____	2 10 ____
5 11 ____	8 11 ____	4 9 ____	5 7 ____
8 13 ____	4 12 ____	6 10 ____	1 6 ____
9 17 ____	2 6 ____	3 9 ____	6 7 ____
4 13 ____	1 3 ____	6 9 ____	9 15 ____
3 7 ____	9 10 ____	3 9 ____	4 13 ____
1 4 ____	8 17 ____	2 5 ____	8 12 ____
2 3 ____	3 11 ____	9 11 ____	5 13 ____
6 8 ____	5 8 ____	1 10 ____	9 14 ____
3 9 ____	6 11 ____	8 9 ____	2 11 ____
4 7 ____	9 15 ____	5 13 ____	6 8 ____
8 12 ____	8 17 ____	4 9 ____	1 7 ____
9 17 ____	4 12 ____	9 13 ____	3 4 ____
5 14 ____	3 7 ____	6 15 ____	4 7 ____
1 6 ____	2 5 ____	2 8 ____	2 6 ____
2 3 ____	5 7 ____	4 6 ____	3 5 ____
8 10 ____	1 6 ____	3 7 ____	9 12 ____
1 9 ____	6 7 ____	5 8 ____	5 14 ____
2 3 ____	1 7 ____	8 13 ____	6 11 ____
5 7 ____	8 9 ____	1 9 ____	8 14 ____
3 8 ____	5 13 ____	5 6 ____	1 9 ____
9 12 ____	6 11 ____	6 11 ____	6 7 ____
6 15 ____	3 9 ____	9 15 ____	4 10 ____
4 10 ____	2 5 ____	8 17 ____	9 13 ____
3 7 ____	9 11 ____	3 11 ____	2 11 ____
6 9 ____	4 13 ____	1 4 ____	3 5 ____
# Correct ____	# Correct ____	# Correct ____	# Correct ____

Reliability Code ____

Test Completion Code ____

Impairment Code ____ ____ ____

Follow Up Point

Form 8. American Congress of Rehabilitation Medicine Definition of Mild Traumatic Brain Injury

Definition of mild traumatic brain injury

Developed by the Mild Traumatic Brain Injury Committee of the Head Injury Interdisciplinary Special Interest Group of the American Congress of Rehabilitation Medicine

Definition

A patient with mild traumatic brain injury is a person who has had a traumatically induced physiological disruption of brain function, as manifested by at least one of the following:

1. any period of loss of consciousness;

2. any loss of memory for events immediately before or after the accident;

3. any alteration in mental state at the time of the accident (eg, feeling dazed, disoriented, or confused); and

4. focal neurological deficit(s) that may or may not be transient;
but where the severity of the injury does not exceed the following:
• loss of consciousness of approximately 30 minutes or less;
• after 30 minutes, an initial Glasgow Coma Scale (GCS) of 13–15; and • posttraumatic amnesia (PTA) not greater than 24 hours.

Comments

This definition includes:

1. the head being struck,

2. the head striking an object, and

3. the brain undergoing an acceleration/deceleration movement (ie, whiplash) without direct external trauma to the head.

It excludes stroke anoxia, tumor, encephalitis, etc. Computed tomography, magnetic resonance imaging, electroencephalogram, or routine neurological evaluations may be normal. Due to the lack of medical emergency, or the realities of certain medical systems, some patients may not have the above factors medically documented in the acute stage. In such cases, it is appropriate to consider symptomatology that, when linked to a traumatic head injury, can suggest the existence of a mild traumatic brain injury.

Symptomatology

The above criteria define the event of a mild traumatic brain injury. Symptoms of brain injury may or may not persist, for varying lengths of time, after such a neurological event. It should be recognized that patients with mild traumatic brain injury can exhibit persistent emotional, cognitive, behavioral, and physical symptoms, alone or in combination, which may produce a functional disability. These symptoms generally fall into one of the following categories, and are additional evidence that a mild traumatic brain injury has occurred:

1. physical symptoms of brain injury (eg, nausea, vomiting, dizziness, headache, blurred vision, sleep disturbance, quickness to fatigue, lethargy, or other sensory loss) that cannot be accounted for by peripheral injury or other causes;
2. cognitive deficits (eg, involving attention, concentration, perception, memory, speech/ language, or executive functions) that cannot be completely accounted for by emotional state or other causes; and
3. behavioral change(s) and/or alterations in degree of emotional responsivity (eg, irritability, quickness to anger, disinhibition, or emotional lability)
   that cannot be accounted for by a psychological reaction to physical or emotional stress or other causes.

Comments

Some patients may not become aware of, or admit, the extent of their symptoms until they attempt to return to normal functioning. In such cases, the evidence for mild traumatic brain injury must be reconstructed. Mild traumatic brain injury may also be overlooked in the face of more dramatic physical injury (eg, orthopedic or spinal cord injury). The constellation of symptoms has previously been referred to as minor head injury, post-concussive syndrome, traumatic head syndrome, traumatic cephalgia, post-brain injury syndrome and posttraumatic syndrome.

Contributing Authors

Thomas Kay, PhD, Senior Contributor
Douglas E. Harrington, PhD,
Committee Chair Richard Adams, MD
Thomas Anderson, MD
Sheldon Berrol, MD
Keith Cicerone, PhD
Cynthia Dahlberg, MA, CCC
Don Gerber, PhD
Richard Goka, MD
Preston Harley, PhD
Judy Hilt, RN
Lawrence Horn, MD
Donald Lehmkuhl, PhD
James Malec, PhD

http://www.acrm.org/wp-content/uploads/pdf/TBIDef_English_10-10.pdf

Form 9. Marshall CT Classification Chart. (from Marshall et al. 1992)

TABLE 1. DIAGNOSTIC CATEGORIES OF TYPES OF ABNORMALITIES VISUALIZED ON CT SCANNING

Diffuse injury I (no visible pathologic change)	No visible intracranial pathologic change seen on CT
Diffuse injury II	Cisterns are present with shift 0–5 mm and/or Lesion densities present No high or mixed density lesion > 25 ml May include bone fragments and foreign bodies.
Diffuse injury III (swelling)	Cisterns compressed or absent with shift 0–5 mm No high or mixed density lesion > 25 ml
Diffuse injury IV (shift)	Shift > 5 mm No high or mixed density lesion > 25 ml
Evacuated mass lesion	Any surgically evacuated lesion
Non evacuated mass lesion	High or mixed density lesion > 25 ml, not surgically evacuated
Brain dead	No brainstem reflexes Flaccidity Fixed and nonreactive pupils No spontaneous respirations with a normal $PaCO_2$ Spinal reflexes permitted

REFERENCES

Adoni, A., & McNett, M. (2007). The pupillary response in traumatic brain injury: A guide for trauma nurses. *Journal of Trauma Nursing, 14*, 191-196.

Anderson, S.I., Housley, A. M., Jones, P. A., Slattery, J, & Miller, J. D. (1993). Glasgow outcome scale: an inter-rater reliability study. *Brain Injury,* **7:** 309-317**.**

Armstrong, V. (2010). *Outcome prediction following severe traumatic brain injury: comparison of the Disability Rating Scale (DRS) and Glasgow Outcome Scales (GOSS and GOSE).* (Unpublished doctoral dissertation). University of Houston, Houston, Texas.

Audoin, B., Ibarrola, D., Au Duong, M. V., Pelletier, J., Confort-Gouny, S., Malikova, I., Ali-Cherif, A., Cozzone, P. J. & Ranjeva, J.-P. (2001.) Functional MRI study of PASAT in normal subjects. *Magma,* **18:** 96-102.

Bate, A. J., Mathias, J. L. & Crawford, J. R. 2001. Performance on the Test of Everyday Attention and standard tests of attention following severe traumatic brain injury. *The Clinical Neuropsychologist,* **15:** 405-422.

Benedict, R. H. B., Cookfair, D., Gavett, R., Gunther, M., Munschauer, F., Garg, N. & Weinstock-Guttman, B. (2006). Validity of the minimal assessment of cognitive function in multiple sclerosis (MACFIMS). *Journal of the International Neuropsychological Society,* **12:** 549-558.

Biney, F. O. 2010. *The relationship between blood alcohol level and global outcome of individuals with severe traumatic brain injury.* (Unpublished doctoral dissertation). University of Houston, Houston, Texas.

Choi, S. C., Ward, J. D. & Becker, D. P. 1983. Chart for outcome prediction in severe head injury. *Journal of Neurosurgery,* **59:** 294-297.

Choi, S. C., Marmarou, A., Bullock, R., Nichols, J. S., Wei, X., Pitts, L. H. & The American Brain Injury Consortium Study Group. (1998). Primary end points in Phase III clinical trials of severe head trauma: DRS versus GOS. *Journal of Neurotrauma,* **10:** 771-776.

Christodoulou, C., DeLuca, J., Ricker, J. H., Madigan, N. K., Bly, B. M., Lange, G., ... & Ni, A. C. (2001). Functional magnetic resonance imaging of working memory impairment after traumatic brain injury. *Journal of Neurology, Neurosurgery & Psychiatry*, **71:** 161-168.Corrigan, J.D., Selassie, A. W. & Orman, J.A. (2010). The Epidemiology of Traumatic Brain Injury. *Journal of Head Trauma Rehabilitation,* **25:** 72-80.

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 and Rehabilitation*, **84**: 1449-1457.

Eliason, M. R., & Topp, B. W. (1984). Predictive validity of Rappaport's Disability Rating Scale in subjects with acute brain dysfunction. *Physical Therapy*, **64**: 1357-1360.

Ewing-Cobbs, L., et al. (2004). Modeling of longitudinal academic achievement scores after pediatric traumatic brain injury. *Developmental Neuropsychology,* **25:** 107-133.

Field, A. (2011). Discovering statistics using SPSS. 3rd Edition. Sage Publications, Los Angeles, USA.

Forn, C., Ventura-Campos, N., Belenguer, A., Belloch, V., Parcet, M. A., & Avila, C. (2008). A comparison of brain activation patterns during covert and overt paced auditory serial addition test tasks. *Human Brain Mapping*, **29:** 644-650.

Francis, D. J., Schatschneider, C., & Carlson, C. D. (2000). Introduction to individual growth curve analysis. In *Handbook of research in pediatric and clinical child psychology* (pp. 51-73). Springer US.

Giacino, J. T., Kezmarsky, M. A., DeLuca, J., & Cicerone, K. D. (1991). Monitoring rate of recovery to predict outcome in minimally responsive patients. *Archives of Physical Medicine and Rehabilitation*, **72:** 897-901.

Gouvier, W. D., Blanton, P. D., LaPorte, K. K., & Nepomuceno, C. (1987). Reliability and validity of the Disability Rating Scale and the Levels of Cognitive Functioning Scale in monitoring recovery from severe head injury. *Archives of Physical Medicine and Rehabilitation*, **68:** 94-97.

Gronwall, D. M. A.; Sampson, H. The psychological effects of concussion. Auckland, New Zealand: Auckland University Press; 1974.

Gronwall, D. & Wrightson, P. (1981). Memory and information processing capacity after closed head injury. *Journal of Neurology, Neurosurgery and Psychiatry*, **44:** 889-895.

Hall, K. M., Cope, D. N., & Rappaport, M. (1985). Glasgow Outcome Scale and Disability Rating Scale: comparative usefulness in following recovery in traumatic head injury. *Archives of Physical Medicine and Rehabilitation*, **66**: 35-37.

Hall, K. M., Hamilton, B. B., Gordon, W. A., & Zasler, N. D. (1993). Characteristics and comparisons of functional assessment indices: disability rating scale, functional independence measure, and functional assessment measure. *The Journal of Head Trauma Rehabilitation*, **8:** 60-74.

Hattori, N., Swan, M., Stobbe, G. A., Uomoto, J. M., Minoshima, S., Djang, D., Krishnananthan, R. & Lewis, D. H. 2009. Differential SPECT activation patterns associated with PASAT performance may indicate frontocerebellar functional dissociation in chronic mild traumatic brain injury. *The Journal of Nuclear Medicine,* **50:** 1054-1061.

Heilman, M. K. M., & Valenstein, E. (Eds.). (2011). *Clinical neuropsychology*. Oxford University Press.

Higginson, C. I., Arnett, P. A., & Voss, W. D. (2000). The ecological validity of clinical tests of memory and attention in multiple sclerosis. *Archives of Clinical Neuropsychology*, **15**: 185-204.

Hiscock, M., Caroselli, J. S. & Kimball, L. E. (1998). Paced Serial Addition: modality-specific and arithmetic-specific factors. *Journal of Clinical and Experimental Neuropsychology*, **20:** 463-472.

Jennett, B., & Bond, M.R. (1975). Assessment of outcome after severe brain damage. *Lancet*, **1:** 480–484.

Jennett, B., Snoek, J., Bond, M. R. & Brooks, N. (1981). Disability after severe head injury: observations on the use of the Glasgow Outcome Scale. *Journal of Neurology, Neurosurgery and Psychiatry,* **44:** 285-293.

Kay, T., Cavallo, M. M., Ezrachi, O. & Vavagiakis, P. (1995). The Head Injury Family Interview: A clinical and research tool. *The Journal of Head Trauma Rehabilitation*, 10: 12-31.

King, N. S. 1996. Emotional, neuropsychological, and organic factors: their use in the prediction of persisting postconcussion symptoms after moderate and mild head injuries. *Journal of Neurology, Neurosurgery, and Psychiatry,* **61:** 75-81.

Larrabee, G. J. & Curtiss, G. (1995). Construct validity of various verbal and visual memory tests. *Journal of Clinical and Experimental Neuropsychology,* **17:** 536-547.

Levin, H.S., Mattis, S., Ruff, R. M., Eisenber, H. M., Marshall, L. F., Tabaddor, K., High, W. M. & Frankowski, R. F. (1987). Neurobehavioral outcome following minor head injury: a three-center study. *Journal of Neurosurgery,* **66:** 234-243.

Levin, H.S., Gary, H. E., Eisenberg, H. M., Ruff, R. M., Barth, J. T., Kreutzer, J., High, W. M., Portman, S., Foulkes, M. A., Jane, J. A., Marmarou, A. & Marshall, L. F. (1990). Neurobehavioral outcome 1 year after severe head injury. *Journal of Neurosurgery,* **73:** 699-709.

Levin, H.S., Boake, C., Song, J., McCauley, S., Contant, C., Diaz-Marchan, P., Brundage, S., Goodman, H. & Kotrla, K. J. (2001a). Validity and sensitivity to change of the Extended Glasgow Outcome Scale in mild to moderate traumatic brain injury. *Journal of Neurotrauma,* **18**: 575-584.

Levin, H.S., Song, J., Ewing-Cobbs, L., Chapman S.B. & Mendelsohn D. (2001b). Word fluency in relation to severity of closed head injury, associated frontal brain lesions, and age at injury in children. *Neuropsychologia,* **39:** 122-131.

Lezak, M.D., Howieson, D.B., Bigler, E.D. & Tranel, D. (2012). Neuropsychological assessment. 5th Edition. Oxford University Press, USA.

Maas, A. I., Steyerberg, E. W., Butcher, I., Dammers, R., Lu, J., Marmarou, A., ... & Murray, G. D. (2007). Prognostic value of computerized tomography scan characteristics in traumatic brain injury: results from the IMPACT study. *Journal of Neurotrauma*, *24*(2), 303-314.

Marmarou, A., Lu, J., Butcher, I., McHugh, G. S., Murray, G. D., Steyerberg, E. W., ... & Maas, A. I. (2007). Prognostic value of the Glasgow Coma Scale and pupil reactivity in traumatic brain injury assessed pre-hospital and on enrollment: an IMPACT analysis. *Journal of Neurotrauma*, *24*(2), 270-280.

Marshall, L. F., Marshall, S. B., Klauber, M. R., Clark, M. V. B., Eisenberg, H. M., Jane, J. A., ... & Foulkes, M. A. (1991). A new classification of head injury based on computerized tomography. *Special Supplements*, *75*(1S), S14-S20.Marshall et al. 1992

McCauley, S.R., Hannay, H.J., & Swank, P.R. (2001). Use of the Disability Rating Scale recovery curve as a predictor of psychosocial outcome following closed-head injury. *Journal of the International Neuropsychological Society,* **7:** 457-467.

McNett, M. (2007). A review of the predictive ability of Glasgow Coma Scale Scores in Head-Injured Patients. *Journal of Neuroscience Nursing,* **39:** 68-75.

Menon, D. K., Schwab, K., Wright, D. W. et al. (2010). Position statement: Definition of traumatic brain injury. *Archives of Physical Medicine and Rehabilitation*, **91:** 1637-1640.

Neese, L. E., Caroselli, J. S., Klaas, P., High, W. M., Becker, L. J., & Scheibel, R. S. (2000). Neuropsychological assessment and the Disability Rating Scale (DRS): a concurrent validity study.*Brain Injury,* **14:** 719-724.O'Donnell, J. P., MacGrego, L. A., Dabrowski, J. J., Oestreicher, J. M. & Romero, J. J. (1994).Construct validity of neuropsychological tests of conceptual and attentional abilities. *Journal of Clinical Psychology,* **50:** 596-600.

O'Donnell, J. P., MacGregor, L. A., Dabrowski, J. J., Oestreicher, J. M., & Romero, J. J. (1994). Construct validity of neuropsychological tests of conceptual and attentional abilities. *Journal of Clinical Psychology*, **50:** 596-600.

Pastorek, N. J., Hannay, H. J. & Contant, C. S. (2004). Prediction of global outcome with acute neuropsychological testing following closed-head injury. *Journal of the International Neuropsychological Society*, **10:** 807-817.

Pettigrew, L. E., Wilson, J. T. & Teasdale, G.M. (1998). Assessing disability after head injury: improved use of the Glasgow Outcome Scale. *Journal of Neurosurgery,* **89:** 939-943.

Ponsford, J. & Kinsella, G.1992. Attentional deficits following closed-head injury. *Journal of Clinical and Experimental Neuropsychology,* **14:** 822-838.

Rappaport, M., Hall, K.M., Hopkins, K., Bellza, T. & Cope, D.N. (1982). Disability Rating Scale for severe head trauma: coma to community. *Archives of Physical Medicine and Rehabilitation*, **63:** 118-124.

Satz, P., Zaucha, K., Forney, D. L., McCleary, C., Asarnow, R. F., Light, R., Levin, H., Kelly, D., Bergsneider, M., Hovda, D., Martin, N., Caron, M. J., Namerow, N. & Becker, D. (1998). Neuropsychological, psychosocial and vocational correlates of the Glasgow Outcome Scale at 6 months post-injury: a study of moderate to severe traumatic brain injury patients. *Brain Injury*, **12:** 555-567.

Scranton, J., Fogel, M. L. & Erdman, W. J. (1970). Evaluation of functional levels of patients during and following rehabilitation. *Archives of Physical Medicine and Rehabilitation,* **51:** 1-21.

Servadei, F., Nasi, M., Giuliani, G., Cremonini, A., Cenni, P., Zappi, D., et al. (2000). CT prognostic factors in acute subdural haematomas: the value of the 'worst' CT scan. *British Journal of Neurosurgery*, **14:** 110-116.

Sherman, E. M. S., Strauss, E. & Spellacy, F. (1996). Validity of the paced auditory serial addition test (pasat) in adults referred for neuropsychological assessment after head injury. *The Clinical Neuropsychologist*, **11:** 34-45.

Strauss, E., Sherman, E.M.S. & Spreen, O. (Eds.) (1998). A compendium of neuropsychological tests: Administration, norms and commentary. 3rd Edition. Oxford University Press; USA**.**

Stover, S. L., & Zeiger Jr, H. E. (1976). Head injury in children and teenagers; functional recovery correlated with the duration of coma. *Archives of Physical Medicine and Rehabilitation*, *57*(5), 201-205.

Struchen, M. A., Hannay, H. J., Contant, C. F. & Robertson, C. S. 2001. The relation between acute physiological variables and outcome on the Glasgow Outcome Scale and Disability Rating Scale following severe traumatic brain injury. *Journal of Neurotrauma,* **18:** 115-125.

Teasdale, G. & Jennett, B. (1974). Assessment of coma and impaired consciousness. *Lancet,* **ii**: 81-84.

Teasdale, G. M., Pettigrew, L. E. L., Wilson, J. T. L., Murray, G & Jennett, B. 1998. Analyzing outcome of treatment of severe head injury: a review and update on advancing the use of the Glasgow Outcome Scale. *Journal of Neurotrauma,* **15:** 587-597.

Tombaugh, T. N. (2006). A comprehensive review of the Paced Auditory Serial Addition Test (PASAT). *Archives of Clinical Neuropsychology,* **21**: 53-76.

Tombaugh, T. N., Stormer, P., Rees, L., Irving, S. & Francis, M. (2006). The effects of mild and severe traumatic brain injury on the auditory and visual versions of the Adjusting-Paced Serial Addition Test (Adjusting-PSAT). *Archives of Clinical Neuropsychology,* **21**: 753-761.

Tüdös, Z., Hok, P., Hrdina, L., & Hluštík, P. (2014). Modality effects in paced serial addition task: Differential responses to auditory and visual stimuli. *Neuroscience*, **272:** 10-20.

Vanderploeg, R. D., Curtiss, G., & Belanger, H. G. (2005). Long-term neuropsychological outcomes following mild traumatic brain injury. *Journal of the International Neuropsychological Society*, **11:** 228-236.

Veramonti, T. (2005). The assessment of impaired awareness of deficits at three months post traumatic brain injury. (Unpublished doctoral dissertation). University of Houston, Houston, Texas.

Wilson, J. T., Pettigrew, L. E. L. & Teasdale, G. M. (1998). Structured interviews for the Glasgow Outcome Scale and the Extended Glasgow Outcome Scale: guidelines for their use. *Journal of Neurotrauma*, **15:** 573-585.