WORKING MEMORY DIFFERENCES IN PEDIATRIC MODERATE AND SEVERE TRAUMATIC BRAIN INJURY

APPROVED BY SUPERVISORY COMMITTEE

DEDICATION

I would like to thank the members of my Graduate Committee and my family for their continued patience and support.

WORKING MEMORY DIFFERENCES IN PEDIATRIC MODERATE AND SEVERE TRAUMATIC BRAIN INJURY

by

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WORKING MEMORY DIFFERENCES IN PEDIATRIC MODERATE AND SEVERE TRAUMATIC BRAIN INJURY

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Traumatic brain injury is one of the leading causes of disability and impairment in children and adolescents. This study sought to determine the effects of severity on verbal working memory and verbal short-term memory. It was hypothesized that increased severity of injury would be associated with decreased performance on working memory tasks. Participants, aged 6-16 years, were tested 6 to 12 months after injury. The sample was comprised of 12 children and adolescents who had sustained a severe TBI and 11 children and adolescents who had sustained a moderate TBI. Results indicated that there were no significant differences

between the moderately injured group and subjects with severe injuries on tasks of verbal working memory or verbal short-term memory. However, inspection of the data indicated that children in the severe group performed in the Low Average range, while children in the moderate group performed in the Average range. Results may be limited by the small sample size.

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Chapter I

Introduction

Traumatic Brain Injury is one of the most prevalent causes of death and disability in the pediatric population. Over one million children sustain a brain injury each year (Langlois, Rutland-Brown, Thomas, 2005). These children suffer difficulties in many areas, including neurocognitive domains. Many research studies have examined the effect that TBI has on various areas of a child's daily living.

Hanten et al. (2004) researched and found that children who have sustained a traumatic brain injury displayed problems in adaptive and behavioral functioning, as well as executive functioning. Executive functioning is highly susceptible to brain dysfunction following a traumatic brain injury. Executive functioning is the ability to carry out goal-directed behaviors, plan, problem-solve, and demonstrate appropriate behavior (Sesma, Slomine, Ding, & McCarthy, 2008). Deficits in executive functioning may lead to a child experiencing difficulties at school and at home. A study conducted by van Heugten et al. (2006) found that one year after injury deficits in executive functioning remained while other cognitive functions improved.

Executive functioning can be divided into several subcomponents including short-term memory and working memory. Research has shown that children who sustained severe traumatic brain injuries had impairment in the ability to learn and recall words (Shum, Harris, & O-Gorman, 2002). Anderson and Catroppa (2007) found a degree of memory impairment in complex auditory-verbal memory that was present in those with severe TBI. Mandalis et al. (2007) found that children who had suffered a traumatic brain injury had significantly poorer results on Digits Forward of the Digit Span subtest (Wechsler Intelligence Scale for Children – Third Edition: WISC-III, Wechsler, 1991), while Anderson and Catroppa (2007) found the opposite results. Working memory is also affected by a traumatic brain injury. The research is inconsistent as to the effect that severity has on this domain. Children with severe TBI have significant working memory impairments (Mandalis et al., 2007; Roncadin et al., 2004; van Heugten et al., 2006), and children with moderate TBI have working memory impairments but to a lesser extent (Mandalis et al., 2007; Roncadin et al., 2004).

The aim of this study was to determine the working memory differences between moderate and severe traumatic brain injury in the pediatric population. This study will test the following hypotheses: (1) there will be significant differences between the severity groups on measures of verbal working memory and verbal short-term memory; (2) children with severe traumatic brain injury will show more impairment than children with moderate TBI on the BRIEF Working Memory Scale (Gioia, Isquith, Guy, & Kenworthy, 2000); (3) children with severe traumatic brain injury will show more impairment than children with moderate TBI on the WISC-IV Working Memory Index (Wechsler, 2003); and

(4) children with severe traumatic brain injury will demonstrate more impairment than children with moderate TBI on the CVLT-C (Delis, Kramer, Kaplan, & Ober, 1994) Trial 1.

Chapter II

Review of the Literature

Prevalence, Incidence, and Economic Burden

Traumatic Brain Injury (TBI) in the pediatric population is one of the leading causes of lifelong disability and impairments. More than one million children experience a traumatic brain injury each year, and the highest number of injuries in children occurs in two peaks: between ages 0 and 4, and 15 and 24 (Langlois, Rutland-Brown, Thomas, 2005). Males are twice as likely as females to sustain a TBI (Langlois, Rutland-Brown, Thomas, 2005). Traumatic brain injuries are the leading cause of death and disability in children and young adults (Furlow, 2006). About 2,685 children die each year as a result of a TBI (Langlois, Rutland-Brown, Thomas, 2005). For children with a severe TBI, the mortality rate is between 20% and 36.5% (Campbell, Kuehn, Richards, Ventureyra, & Hutchison, 2004; Figaji, Fieggen, Argent, Leroux, & Peter, 2008; Luerssen, Klauber, & Marshall, 1988).

According to the Centers for Disease Control, roughly 435,000 children visit the emergency room each year due to TBI, and 37,000 require hospitalization (Langlois, Rutland-Brown, Thomas, 2005). Many TBIs will go undocumented, undiagnosed, and the children will never see medical professionals (Arciniegas & McAllister, 2008; Hooper, et al., 2004). According to McKinlay et al. (2008), roughly 28.9% of the population sustained four or more TBIs in their lifetime.

Traumatic brain injuries cost between $325,000 and $4,000,000 in lifetime costs for a single TBI. The estimated total economic burden ranges from $37 billion to $159 billion in medical expenses and lost productivity annually (Kraus et al., 2005).

Definition and Types of Traumatic Brain Injury

Traumatic brain injuries are caused by damage to the brain from an outside source, such as a fall or motor vehicle accident that causes a disruption in normal neurological functioning (Langlois, Rutland-Brown, Thomas, 2005). Damage can result from skull penetration, striking the skull, or rapid acceleration or deceleration of the brain. When a child experiences a non-penetrating brain injury, the child's age at the time of injury does not have a significant relationship with the outcome, based on a scale ranging from good recovery to death (Levin, 2003; Berger, Pitts, Lovely, Edwards, & Bartkowski, 1985; Braakman, Gelpke, Habbema, Maas, & Minderhoud, 1980; Bruce, Schut, Bruno, Wood, & Sutton, 1978), but higher rates of mortality and morbidity tend to be present in infants and preschoolers (Jennett, et al., 1979; H. S. Levin, et al., 1992; Luerssen, et al., 1988).

Traumatic brain injuries result from a number of causes. The most common cause for TBI in children is a fall, which accounts for 28% of pediatric injuries, followed by motor vehicle accidents (20%), being struck by an object (19%), and assault or abuse (11%)(Langlois, Rutland-Brown, Thomas, 2005).

Sports-related injuries are also common in the pediatric population (Purcell & Carson, 2008). Falls, motor vehicle collisions, and sports-related injuries are the leading cause of injuries in children over one year old, and in children less than 1 year old TBI resulting from non-accidental injury is the leading cause of death and morbidity (Bishop, 2006; Langlois, Rutland-Brown, Thomas, 2005).

Mechanisms

When a child sustains a brain injury, many different things can happen. The injury can be penetrating, open, or a closed-head injury. A penetrating head injury is an open head wound caused by an object that penetrates the skull and the brain (Furlow, 2006). This type of injury is very common in active military personnel (Furlow, 2006). One example of a penetrating brain injury is a bullet wound to the head.

An open-head injury is diagnosed when the patient's skull is depressed and the meninges are broken. A depressed skull fracture results from a major force breaking the skull and pressing it into the brain, and children who sustain a depressed skull are at higher risk for seizures (Atabaki, 2007).

A basilar skull fracture is the result of a fracture to the temporal bone which can result in blood pooling in the mastoid air cells. A basilar fracture presents with "raccoon eyes" and venous sinus drainage. Cerebrospinal fluid may also leak from the patient's eyes and ears (Atabaki, 2007; Kumar & Mahaparta, 2009). Basilar fractures are present in about 5% of pediatric TBI (Kumar &

Mahapatra, 2009). Often times, these injuries require a neurosurgical intervention or evaluation to repair and elevate the skull (Atabaki, 2007).

A closed-head injury is one in which the brain is injured without penetration to the skull or the dural layer (Atabaki, 2007; Kirkwood, et al., 2008). There are many different types of injuries to the brain that can occur in closed-head injuries. Those injuries include diffuse axonal injuries (DAIs), hematomas, and contusions.

Diffuse Axonal Injury. Diffuse axonal injury (DAI) is defined as a shearing of cell connections due to rapid acceleration and deceleration of the brain (Furlow, 2006), and causes swelling of the neuronal fibers secondary to the tearing (Visocchi, Chiaretti, Genovese, & Di Rocco, 2007). DAI frequently leads to an increase in intracranial pressure (ICP) (Atabaki, 2007). DAI can also stretch the axons in a uniaxial (stretching in one direction) or biaxial (simultaneously stretching in two directions) pattern (Geddes-Klein, Schiffman, & Meaney, 2006; Pfister, Weihs, Betenbaugh, & Bao, 2003). DAI can result in global or widespread damage (Furlow, 2006). Adams et al. (1989) found that DAI can be classified into three grades: damage to axons without gross hemorrhage, damage to axons with hemorrhage in the corpus callosum, and damage to axons in the dorsal part of the brainstem. In children, hemorrhages are not commonly found with damage to the axons due to elasticity of blood vessels (Case, 2008). Functionally, DAI can result in a number of long term problems including attention problems, memory problems, and behavioral changes (Furlow, 2006). Diffuse damage can interrupt cerebral development, such as neuronal myelination and frontal lobe maturation that occurs rapidly during a child's first five years (Anderson et al., 2006).

Hematoma. A hematoma is a blood clot resulting from leaking blood collecting in a confined area of the brain, and causes damage to the surrounding tissue. It can be epidural, intracerebral, or subdural. An epidural hematoma is a bleed that occurs between the dura mater and the skull, and occurs with 2-3% of all pediatric TBI (Kumar & Mahapatra, 2009). Intracerebral hematomas are bleeds that occur within the brain tissue itself. A subdural hematoma is a bleed in the veins in the subdural space, between the dura mater and the brain. Because this type of hematoma can rapidly occupy space, it may cause a rapid increase in intracranial pressure (Case, 2008). Subdural hematomas are associated with poorer outcome and more severe injury (Chung, et al., 2006). After suffering a subdural hematoma and losing consciousness, surgical intervention may be required due an increased risk of possible underlying brain injury (Atabaki, 2007). The frequency of TBIs involving subdural hematomas decrease as age increases throughout childhood (Luerssen, et al., 1988).

Contusion. Another type of injury is a cerebral contusion. A contusion occurs when blunt force causes damage to blood vessels in the brain which causes blood to seep into brain tissue (Ragaisis, 2002), and commonly occur in the cortical tissue (Atabaki, 2007). Contusions can be either small or large, and can lead to minor symptoms or cerebral edema and increased intracranial pressure (Atabaki, 2007). Contusions are somewhat more common in the temporal and frontal lobes because of the brain being forced into the front of the skull (Furlow, 2006). The skull has a rough surface that contributes to the damage (Lezak, 1995).

Concussion. A concussion is defined as a mild blow to the head that can cause shearing of brain cells that is undetectable by CT scans or MRIs, and may imply a brief loss or alteration of consciousness (Kirkwood, et al., 2008). Some of the most common symptoms of a concussion include headaches, dizziness, fatigue, nausea, confusion, irritability and difficulty concentrating (Atabaki, 2007; Campbell, et al., 2004; Kirkwood, et al., 2008). Symptoms are commonly acute in onset and present as more functional disturbances rather than structural (Atabaki, 2007). The Concussion in Sport Group, a panel including physicians, neurologists, sports medicine physicians, trauma surgeons and members of other related fields, defined a concussion as “a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces” (Aubry et al., 2002; McCrory et al., 2005). Concussions are typically thought of as self-limited impairment of neurological functioning with associated clinical symptoms (Atabaki, 2007).

Secondary Injury

Intracranial Pressure

Secondary injuries after a traumatic brain injury can cause as much damage as the initial injury, and are indirect results of the injury. For example, intracranial pressure (ICP) may increase in the hours or days following TBI, and higher ICP has been associated with poorer outcome (Carter, Butt, & Taylor, 2008; Orliaguet, Meyer, & Baugnon, 2008). ICP is monitored to maintain an adequate cerebral perfusion pressure (CPP). ICP is best monitored by inserting a ventricular catheter to an external strain gauge, but if the brain swelling is too severe, parenchymal ICP monitoring may be done with fiberoptic or strain gauge catheter tip transduction (Carter, et al., 2008; Orliaguet, et al., 2008). Carter et al. (2008) found that ICP should be kept below 20mmHg and the CPP should be kept above 40mmHg. When the ICP is increased or CPP is decreased, the study found that the outcomes were not favorable.

Autoregulation

Cerebral autoregulation is the body's ability to monitor and keep appropriate blood pressure in the cerebrum despite changes in the CPP (Ragašis, 2002). Freeman and colleagues (2008) studied cerebral autoregulation in children and compared the incidence rate of impaired cerebral autoregulation to the injury severity. The study found that children less than four years old and children with low GCS scores showed signs of impaired cerebral autoregulation. These risk factors lead to a worse long-term outcome, and added with hypotension or hypertension will lead to cerebral ischemia or cerebral hyperemia, respectively.

Hypotension

A study on hypotension found that there is a clear correlation between hypotension in the first six hours after a traumatic brain injury and outcome (Samant et al., 2008). Campbell et al. (2004) investigated medical prognosticators for mortality and cognitive functioning in children during the three years after their injury and found that medical complications, such as seizures, headaches, behavioral changes, and nosocomial infections, were common. Leurssen et al. (1988) found that for children under the age of 15 with profound hypotension, which is more than 30 mmHg below the expected median for their age, the mortality rate was 33.3% (Luerssen, et al., 1988).

Neuronal Complications

A number of long term medical complications can occur after a traumatic brain injury such as cerebellar and cerebral atrophy. The cerebellum is responsible for coordination, motor control, and some cognitive functions. In a study conducted by Spanos et al. (2007), it was discovered that children with traumatic brain injury had significantly smaller amounts of cerebellar white matter and grey matter than children without TBI. The children with TBI had both focal and diffuse cerebellar insult after the injury and extensive axonal degeneration. The volumetric relationship between the primary structures implicated in pathways projecting to and from the cerebellum indicated that damage in the cerebellum is structure-specific and not simply the result of retrograde degeneration. Ghosh et al. (2009) studied the relationship between the Glasgow Coma Scale score and later cerebral atrophy in children with traumatic brain injury. The study found that the initial GCS score was able to predict later cerebral atrophy, both in the percentage of white matter and ventricle-to-brain ratio.

Measurement of Severity and Outcome of Injury

There is no universal singular method of determining injury severity after a traumatic brain injury, although many variables have been used in the literature to determine severity. Medical professionals use many different variables when determining a patient's injury severity and potential outcome. For example, duration of hospital stay and length of time in a coma are good predictors of the child's outcome (Campbell et al., 2004). Galloway et al. (2008) found that length of time in a coma, days on a ventilator, and length of hospital stay were higher in patients with severe TBI than those with mild or moderate TBI, as classified by the Glasgow Coma Scale (GCS), and these variables were associated with poorer outcomes. The lowest GCS score, number of lesions on CT or MRI imaging, and duration of impaired consciousness were found to be highly predictive of outcome one year after injury (Prasad, Ewing-Cobbs, Swank, & Kramer, 2002). Pupil reactivity is still another variable that has been associated with outcome, with low reactivity associated with worse outcome (Bruce, et al., 1978; Orliaguet, et al., 2008). Abnormal pupil response may be indicative of increased intracranial pressure (ICP), a herniation in the brainstem, or a compression of the third cranial nerve (Atabaki, 2007).

CT scans and Imaging

CT scans are the most common and immediate action taken by emergency departments after a child suffers a head trauma (Atabaki, 2007). CT scans are more sensitive than Magnetic Resonance Imaging (MRI) to detecting skull fractures and have good visualization of focal injuries such as contusions and hematomas (Furlow, 2006). It takes a relatively short period of time to obtain the results and is compatible with acute care equipment and other medical devices (Furlow, 2006). Because the brain will continue to change after TBI in that damage can unfold over time, a CT scan can be falsely reassuring when done immediately following the injury (Orliaguet et al., 2008). Orliaguet et al. (2008) found it important to perform a second CT scan within 24 – 36 hours after admission.

Galloway and colleagues (2008) used diffusion-weighted magnetic resonance imaging (DWI) to determine the outcome after pediatric traumatic brain injury. Diffusion-weighted imaging is a form of magnetic-resonance imaging (MRI). They found that early imaging was superior with the DWI, and the DWI and Apparent Diffusion Coefficient (ADC) values obtained at the time of the injury are predictive of long term outcome. Chung et al. (2006) found that when CT scans found swelling, and subdural and intracerebral hemorrhages, the child was likely to have a worse outcome. CT scans also correlated with initial Glasgow Coma Scale score and the outcome as measured by the Glasgow Outcome Scale (Claret Teruel, et al., 2007).

Rancho Los Amigos

There are several other methods to assess the initial level of functioning after injury to a patient in terms of medical decision-making. A widely used scale for traumatic brain injury is the Rancho Los Amigos scale that was developed at Rancho Los Amigos Hospital (Hagen, Malkmus, Durham, 1979). It is helpful in assessing patients in the first weeks or months following TBI. The Rancho Los Amigos scales measures the level of awareness, cognition, behavior, and interaction with the environment. The levels are based on observation of the patient's response to external stimuli, and provide a descriptive guideline for the various stages that the patient will experience as he or she recovers. There are eight different levels with level I being unresponsive and level VIII being purposeful-appropriate.

This scale has been used by researchers to measure aspects of functioning as a measure of outcome. For example, pediatric patients who had experienced a traumatic brain injury and were given Amantadine had a greater increase in Rancho Los Amigos level during hospital admission (Green, Hornyak, & Hurvitz, 2004). The majority of patients improved in their Rancho Los Amigos scale scores at the time of their discharge from the hospital (Ng & Chua, 2005).

Glasgow Coma Scale

The Glasgow Coma Scale (GCS)(Teasdale & Jennett, 1974) is one of the most widely used tools for assessment of consciousness and has been used by researchers as a predictor of outcome (Braakman, Avezaat, Maas, Roel, & Schouten, 1977). The Glasgow Coma Scale was developed to assess the level of consciousness and to standardize observations in patients who had sustained a head injury. It has been proven to be a quick, accurate, and simple assessment for evaluating neurological functioning (Teasdale, Knill-Jones, & van der Sande, 1978). The Glasgow Coma Scale uses a fifteen point scale based on motor response (ranging from 'no movement' to 'follows commands'), verbal response (ranging from 'no sounds' to 'oriented'), and eye opening (ranging from 'does not open eyes' to 'spontaneous eye opening')(Teasdale & Jennett, 1974). There are different ranks within each category, and it can serve as an assessment of level of consciousness immediately following the injury or any time after. It is widely accepted as a method to evaluate and characterize head injury.

The Glasgow Coma Scale is divided into three levels of severity. A GCS score of 13 – 15 indicates a Mild traumatic brain injury, a score of 9-12 indicates a Moderate TBI, and a score of 3-8 indicates a Severe brain injury (Teasdale, Murray, Parker, & Jennett, 1979). Chung et al. (2006) found that GCS score was the most important predictor of survival, and a score of less than 5 was most likely to have a poor outcome as determined by mortality. When assessed on the Glasgow Coma Scale, only a small percentage of children are categorized as moderate or severe brain injury.

The GCS also has been determined to be a valid predictor of longer term functional outcome. Luerssen, Klauber, and Marshall (1988) indicated that the motor response score in the GCS correlated best with outcome. Chung et al. (2006) found that for the pediatric population, the GCS was more predictive of outcome and had a stronger correlation with outcome when a severe TBI is defined by a 5 or lower. This is due to the lower threshold for neurophysiologic dysfunction. This study also found the GCS to have a receiver operating characteristic curve of 0.991, which indicates that it is a good prognostic tool for predicting the outcome of traumatic brain injuries. The GCS was also found to be the best predictor of a score on the Glasgow Outcome Scale (Chung, et al., 2006). Lower initial GCS was associated with poorer performance on tasks of visual memory and lower nonverbal intelligence (Campbell, et al., 2004).

Outcomes Following Traumatic Brain Injury

Motor Functioning

A traumatic brain injury can have pervasive impact on the physical, educational, behavioral, and cognitive functioning of affected children. The majority of children regain the ability to ambulate independently but may suffer difficulties in walking speed and the amount of energy it takes to walk (Kuhtz-Buschbeck, et al., 2003) Another study by Katz-Leurer, Rotem, Keren, and Meyer (2009) found that independent ambulators had decreased balance performance, increased variability of step length, and decreased gait speed. The researchers also found an inverse relationship between gait speed and gait variability. Children with traumatic brain injury also have an increase in variability gait parameters. Gait parameters are defined as an individual's walking speed, stride length, and step length (Katz-Leurer, Rotem, Lewitus, Keren, & Meyer, 2008). Similarly, Kuhtz-Buschbeck (2003) found that children who sustained TBI performed gait and reaching and grasping tasks at a slower pace with more unstable motor patterns with more variability and coordination difficulties.

Family Burden and Stress

Physical and cognitive deficits are not the only difficulties that children who have experienced a TBI may experience. There is an adjustment that every family has to make in order to help the child continue to improve and recover. Wade and colleagues (1996) found that the degree of perceived family burden and parental problems post-injury were greater in families with a child who had a TBI and reported chronic life stress and maladaptive coping skills. Stancin, Wade, Walz, Yeates, and Taylor (2008) found that parents with older children reported much higher levels of injury-related burden and distress than the parents of younger children. In a study conducted by Anderson et al. (2001), family functioning remained stable over time, and difficulties did not emerge until later in the recovery process. Families of a child with a severe brain injury reported significantly higher levels of family burden and stress after the injury compared with mild and moderate TBI, and the brain injury impacted parents, siblings, and other areas of family life. Wade et al. (2006) found similar results that families with a child with a moderate to severe TBI feel injury-related stress and burdens many years after injury. Group differences were also more significant at 4 to 5 years post-injury, and relatively limited at 1 year post-injury. This may have occurred because long-term effects of the TBI may not emerge until after a period of time. A dose-response relationship, or the change in relationship with an increase in exposure and the stressor, has been found between injury severity and the increase in the perception of family burden and stress, even two and a half years after the injury. As the family is exposed to the changes in their family member with a traumatic brain injury, the perception of family burden will increase, as will their perceived stress. The child's behavior and concurrent family function helped to impact the perception of family burden and stress as well (Anderson et al., 2006).

Parents of children who experienced severe TBI reported more depressive symptoms and psychological distress than parents of children with orthopedic injury (Stancin et al., 2008). Pre-injury family function, child behavior, and child adaptive abilities were identified as important factors that influence the effective family functioning in the long-term after injury (Anderson et al., 2006). Families with a child with a severe TBI endorse experiencing poorer family functioning when there is little social support (Wade et al., 2006).

A number of additional factors are associated with injury severity and outcome. For instance, children with severe TBI were more likely to have lower socioeconomic status, whereas demographics of mild and moderate injury groups were more representative of the population (Anderson et al., 2006; Taylor et al., 2008). A strong association has also been documented between severity of injury and level of functioning in functional domains of memory, educational skills, adaptive abilities and behavioral functioning over 30 months post-injury (Anderson et al., 2006).

Behavior

After a traumatic brain injury, children often experience changes in their behavioral patterns, both at home and in the academic setting. Research by Hawley (2004) found that more than half of children with TBI exhibited behavioral problems, both at home and at school. The study found a significant difference between behavioral problems according to Full Scale IQ (FSIQ) on the WISC-III, with children with behavioral problems having lower FSIQ than those without behavioral problems. Children with TBI had significantly higher levels of maladaptive behaviors than those without injury. If the TBI is not disclosed or known, children who exhibit severe behavioral problems face the risk of being expelled from school or failing without the support required to help them.

Anderson and colleagues (2006) found that all groups of children with TBI had increases in behavior problems, and 20% were clinically significant. The severe TBI group made up over half of this group. Ponsford et al. (1999) studied acute recovery and outcome after mild TBI in school-age children at one week and three months after injury. The study found a clear relationship between pre-injury learning and pre-injury behavioral problems and persisting difficulties in the behavioral domain at three months after injury.

Social Skills. When a child experiences a traumatic brain injury and his/her behavior is affected, impairments in social skills may arise. Hanten and colleagues (2008) found that children with TBI scored lower than controls on a measure of social problem-solving skills through one year post-injury. Hooper et al. (2004) found that problems in social behaviors are not always immediately apparent and may manifest more fully only after a period of time post-injury. Many children have returned to school before the socially inappropriate behaviors fully appear and may not receive the necessary treatment due to unnoticed changes resulting from the traumatic brain injury. Anderson et al. (2006) also found that children with a traumatic brain injury had a tendency to externalize problems and have poorer social skills.

Psychiatric Disturbance and Personality Change. According to a study by Rutter et al. (1983), children with preinjury behavioral problems showed an increased risk of psychiatric disorders postinjury, and over 50% of the children that showed some evidence of preinjury behavioral or psychiatric disorder developed a clinically significant disorder in the 12 months post-injury.

Max et al. (2000) defined personality change in children due to traumatic brain injury as persistent personality disturbance directly related to the physiological effects of TBI, and may manifest as marked deviation from typical development. It must last longer than one year and not be a change in a stable personality pattern. Children in this study were ages 6 to 14 and suffered from a closed head injury. This study defined five subtypes of personality change: affective lability, aggressive, disinhibited, apathetic, and paranoid. Of the severely injured represented, 49% presented with the affective lability subtype, 38% aggressive/disinhibited, 14% apathetic, and 5% paranoid (Max, et al., 1998). The labile and aggressive subtypes almost always co-occurred, and a disinhibited subtype commonly occurred with either labile or aggressive subtypes. Apathetic subtype is often transient, and paranoid subtype is rare (Max, et al., 2000). In a follow-up study (2006), Max et al. found that personality change declined in the first six months after injury from 22% to a stable rate of 12-13% at one to two years post injury. Affective lability remained the most common subtype, followed by aggressive and disinhibited subtypes. The study also found that personality change was comorbid with several categories of new-onset psychiatric disorders including externalizing disorders and internalizing disorders. Personality changes were related to severity of injury, diffuse frontal lobe white matter lesions, and preinjury adaptive functioning (Max et al., 2000, 2006). Persistent personality change was not significantly associated with any concurrent psychosocial adversity variables such as socioeconomic status, family functioning, and family stress (Max et al., 2000).

Kirkwood et al. (2000) found an increase in the rate of depression at six and twelve months after injury in children who had a TBI between 6 and 12 years of age, and the risk was higher in children with a lower socioeconomic status (SES). Children with a lower SES may have fewer resources to aid in their rehabilitation and have less social and familial support to handle the changes and stressors that sometimes accompany a traumatic brain injury.

Intelligence

A number of studies have researched the effects of traumatic brain injury on intellectual functioning, and many have demonstrated a significant impact of severity of TBI on IQ. For example, Campbell and colleagues (2004) found that the Glasgow Coma Scale score was positively correlated with performance IQ on the Wechsler Intelligence Scale for Children-Third Edition (WISC-III: Wechsler, 1991), with children who have more severe injuries continuing to have difficulties with memory and nonverbal problem solving. Verbal IQ has been found to be relatively spared across all severity groups (van Heugten et al., 2006). Ewing-Cobbs et al. (2006) studied the outcome of IQ after early TBI and found that 5 years after injury, children with moderate and severe TBI scored significantly lower on measures of IQ. There was neither an acceleration nor deceleration in the rate of change between 3 and 7 years after injury.

Academic Functioning

While some deficits may lessen in severity and dysfunction over time, many other deficits create more dysfunction and are life-long. Many children with TBI experience problems in an academic setting, and may return to school while still recovering from the resulting deficits. Anderson et al. (2006) found that greater injury severity was correlated with poorer educational performance in reading, arithmetic, and spelling in school age children. This study found that while children with moderate TBI initially tested below average after injury, the group had a tendency to improve over time and at 30 months had moved into the average range. Those with severe TBI had global and persistent educational difficulties even 30 months after the injury on tests of achievement and intellectual abilities. In contrast, children who sustained mild TBI performed at the same level as their non-injured peers (2006).

Both pre-injury educational skills and post-injury memory skills are significant predictors of academic success at 24 months post-injury (Catroppa & Anderson, 2007). Ewing-Cobbs and et al. (2006) conducted a longitudinal study on the IQ and academic outcomes at 5 years after injury. They found that children with TBI scored significantly lower than non-injured children on tests of IQ. Academic achievement test scores were reduced in areas evaluated such as word decoding, reading fluency, and mathematical calculation and retrieval of mathematical facts. The study also found that early TBI had an adverse effect on academic progress and about half of the children in the TBI group failed a grade or needed special education. Many children received rehabilitation in some form, and even with this additional support continued to show difficulties. Taylor et al. (2008) studied school readiness in children 3 years old to 6 years old, and found that compared to controls, children with severe TBI had poorer school readiness skills, but this finding did not extend to moderate and mild TBI.

Arithmetic. As with broad academic functioning, arithmetic ability can be affected by traumatic brain injury. Catroppa and Anderson (2007) found a dose-response relationship between severity of the traumatic brain injury and arithmetic skills with the severe TBI group scored in the “Borderline” to “Low Average” range on the Wide Range Achievement Test – Third Edition (WRAT-III; Stone et al., 1995). A study by Anderson and Catroppa (2005) found that after TBI, arithmetic ability is very likely to suffer and children are likely to perform below grade level at 2 years post-injury. They discussed the difficulties in arithmetic to be due to impairments in working memory and mental flexibility.

Spelling and Reading. Language-based educational performance may also be affected by an injury to the brain. For example, Ewing-Cobbs and colleagues (2006) found performances to be reduced in the areas of spelling, oral comprehension, word decoding, and writing fluency in children with moderate and severe TBI compared to controls. The TBI group also experienced difficulties with language comprehension and processing speed for decoding and producing written text. A more significant injury was associated with poorer performance with reading and spelling, but mild and moderate TBI groups tested in the Average range at 5 years post-injury.

Neurocognitive Complications

Many research studies (Babikian & Asarnow, 2009; Catroppa, Anderson, Morse, Haritou, & Rosenfeld, 2008; van Heugten, et al., 2006; Vriezen & Pigott, 2002) have found deficits in neurocognitive domains. Common neurocognitive impairments following a traumatic brain injury include executive functioning, working memory, and verbal learning. Hooper and colleagues (2004) studied a wide range of symptoms that children can manifest following a TBI. They found that children who presented at emergency departments and inpatient hospitals manifested more neurocognitive symptoms at various stages over ten months following the injury. The neurocognitive problems most often included memory and attention.

Attention

After sustaining a traumatic brain injury, a high percentage of children show increased problems in many areas, including attention and impulse control. Catroppa et al. (2006) in a study of attentional skills following pediatric TBI found that children with TBI have difficulties with multiple task demands in a noisy environment and sustained attention in timed conditions. Hooper et al. (2004), in a study on caregiver reports of symptoms and changes following pediatric traumatic brain injury, found that attention symptoms, along with memory problems, were reported most frequently.

Approximately 15 to 20% of moderate and severe TBI patients have been found to have signs of attention-deficit/ hyperactivity disorder (Levin et al., 2007). According to Levin (2007), ADHD that occurs after TBI in children is often referred to as secondary ADHD (SADHD). Children with SADHD showed an increase in inattentive and hyperactive symptoms in the first six months after injury, and inattentive type was the most common. Many children will begin to exhibit symptoms of ADHD, but TBI and ADHD seem to have different underlying neuropathologies. Kramer et al. (2008) studied underlying neural processes that are components of attention and found that children with ADHD show a reduced activation of relevant neural circuits, while TBI show an increase in these areas. The circuits refer to the brain activation patterns that mediate working memory (Kramer, et al., 2008).

Executive Functioning

Many research studies have examined the level of deficits in executive functioning after a traumatic brain injury. Executive functioning is a person's ability to carry out goal-directed behaviors, problem-solve, plan, and demonstrate appropriate behavior (Sesma et al, 2008). These skills are vital for independent, purposeful, and goal-directed activities (Lezak, 2004). A deficit in executive functioning may lead to difficulties within the home and school.

Donders and Warschausky (2007) studied the neurobehavioral outcomes in both early childhood and late childhood TBI. Early childhood traumatic brain injury was defined as an injury occurring between the ages of 6 and 12. Late childhood TBI was one sustained after 16 years old. The early-onset participants performed more poorly on a measure of high level attention and information processing speed. This group also rated themselves as less socially integrated and friends and family rated them as having less effective executive skills. The two groups did not differ significantly in overall cognitive abilities or vocational and educational accomplishments. The sample size of the early-onset group was small (N=15) compared to the late-onset group and the former group was chosen retrospectively (Donders & Warschausky, 2007).

In a study conducted by van Heugten et al. (2006), 31 children between the ages of 2 and 18 participated to evaluate progress in their neuropsychological functioning several years after their injury, compared to normal functioning. The participants were tested with standardized, direct performance-based measures of executive functioning: the Wisconsin Card Sorting Task (Heaton, 1981) and the Trail Making Test (Reitan, 1971). The study found that most children did improve on cognitive functioning during their first year post-injury, but most had deficits in executive functioning. The participants received a multidisciplinary form of rehabilitation that included physical and cognitive processes. Many of the children had improvements during rehabilitation, but at follow-up their improvements had changed very little. There is a possible selection bias in that there are more females than males in this study and the high attrition rate in the study once consented (van Heugten, et al., 2006). These limitations may lead to lesser generalizability.

In the Hanten et al. (2004) study, children between 2 and 13 years old at the time of injury were divided into two groups of severe TBI and mild TBI, and a control group of normally developing children. Data from direct measures of executive functioning were consistent with impaired executive functioning in metacognition in severe traumatic brain injury. These children may have difficulty organizing their life and learning because of impairments in inhibitory and interference control, problem solving, planning, and discourse processing. The children in this study who have sustained a traumatic brain injury displayed problems in adaptive and behavioral functioning, along with their general executive functioning. The problems were the most significant in those children who suffered a severe TBI. This study did not use a moderate TBI classification that the current study will use.

Anderson and Catroppa (2005) aimed to study the development of executive functioning after pediatric TBI at the time of injury and at 24 months post-injury. This study investigated the recovery and development of executive functioning in the 2 years after injury in children between 8 years old and 12 years old. Seventy-six children were grouped based on severity classification and given several different direct, performance-based measures of executive functioning. This study utilized 4 subcomponents of executive functioning: attentional control, cognitive flexibility of thought and action, strategic planning and problem solving, and concept formation. Participants were given the Digit Span subtest from the WISC-III (Wechsler, 1991) to assess attentional control, Trail Making Test – Part B and the Contingency Naming Test (Anderson, Anderson, Northam, Taylor, 2000) for cognitive flexibility, Complex Figure of Rey (Rey, 1941) for strategic planning and problem solving, and Controlled Oral Word Association Test (COWAT: Spreen & Strauss, 1998) and Similarities from the WISC-III for concept formation. For attentional control, all TBI groups showed a tendency to improve over time which may indicate a recovery of skills or natural child development. In terms of cognitive flexibility, children with severe TBI were slower to complete tasks, but accuracy was similar in all groups. With more complex tasks, the severe TBI group grew less able to cope with the demands and began making more errors. With problem solving, children with severe TBI showed difficulty with understanding complex nonverbal materials. At 24 months, the group had improved significantly and performed on level with the mild and moderate TBI groups. In the concept formation component, there was a significant difference between the mild group and severe group with verbal fluency and concept formation, but all groups improved over time. This study did not utilize a control group and the age range was relatively small.

Mangeot et al. (2002) studied the long-term executive functioning in children who have sustained a TBI using the Behavior Rating Inventory of Executive Functioning (BRIEF; Gioia, Isquith, Guy, & Kenworthy, 2000). The BRIEF is a parent-report measure of executive functioning, used to assess the child's executive functions in the home and school setting. Participants were between the ages of 6 and 12 at the time of injury, and divided into three groups according to their injury classification: Severe TBI, Moderate TBI, and Orthopedic Injury. As predicted, children with severe TBI demonstrated significantly more executive dysfunctions than the controls even 5 years post-injury, and the parents of traumatic brain injured children rated them with significantly more executive dysfunctions than children without traumatic brain injuries. The behavioral problems that parents reported on the BRIEF were found to be related to the broad measures of psychosocial and adaptive functioning. The BRIEF was also able to predict the level of family functioning and perceived burden on the family members after the injury. These results may be impacted by an attrition bias due to a large portion of participants withdrawing from the study, especially those in the lower socioeconomic status. However, attrition is counterbalanced by a large sample size with moderate, severe, and a control group (Mangeot, Armstrong, Colvin, Yeates, & Taylor, 2002).

A study conducted by Sesma and colleagues (2008) examined caregiver responses on the BRIEF to document changes that occur during the first year after traumatic brain injury in executive functioning, and identified predictive variables that lead to greater dysfunction. Executive dysfunction was common in this study; 18 – 38% had clinically significant dysfunction in the first year. The working memory scale on the BRIEF was the most sensitive to severity of injury. Limitations to this study may be the caregiver-reporting on the BRIEF and its susceptibility to caregiver bias, and the inability to calculate the negativity scale due to the limited number of items scored. The negativity scale measures the extent that the caregiver answered in an unusually negative manner, and relates to bias and over-reporting that may occur (Gioia et al., 2000). Similarly to Mangeot et al. (2002), family functioning led to more executive dysfunction and higher perceived burden and stress.

Behavior Rating Inventory of Executive Function

The BRIEF has been tested as a reliable and valid tool to assess aspects of executive functioning that other performance-based tests may not measure

(Mangeot et al., 2002; Sesma et al., 2008). Performance-based tests may overestimate a child's level of executive functioning due to the highly structured and rigid nature of the standardized, individual tests (Sesma et al., 2008). The BRIEF allows for a more daily observation of executive functioning. Vriezen and Pigott (2002) found a lack of correlation between the parent's report on the child's executive functioning and neuropsychological assessments of executive functioning. Where 10-21% of the sample demonstrated clinically significant impairments on performance-based measures of executive functioning, 29-35% had clinically significant impairments on the BRIEF.

In the study conducted by Mangeot et al. (2002), there was no significant difference between groups on the Working Memory scale. Sesma et al. (2008) found that the Working Memory scale was the only scale that demonstrated significant differences between the control group and all 3 TBI groups. While Vriezen & Pigott (2002) compared children who had sustained a moderate or severe traumatic brain injury on their overall performance on neuropsychological assessments and the BRIEF parent ratings, the BRIEF working memory scale was not directly looked at in comparison with performance-based working memory tasks. The components of the BRIEF and its psychometric properties will be discussed in more detail in the Methods section.

Memory

. *Verbal Memory and Visual Memory*

Memory is commonly affected in TBI. Memory comes in many forms and is the brain's ability to store, retain, and recall information. Verbal memory refers to one's memory for words and verbal items and visual memory relates to one's memory for visual experience and mental images. Campbell et al. (2004) researched medical prognosticators for mortality and cognitive functioning during the three years after brain injury. Eighty-three infants, children, and adolescents ages 1 year to 18 years were included in this study; they were grouped based on GCS score into groups of severe TBI and moderate TBI. The authors found that within 15 months of the traumatic brain injury, all children scored more than one standard deviation below the mean on tests of verbal memory, and returned to normal at a later follow-up. This study also found that visual memory was within normal range at all follow-ups, and those with more severe injuries continued to experience difficulty with nonverbal problem solving and memory. As in other domains, a lower GCS was associated with lower nonverbal intelligence and poorer performance on visual memory measures (Campbell, et al., 2004). A limitation of this study is the inability to quantify the true measure of severity in using solely the Glasgow Coma Scale score. When combined with other severity factors, there is a possibility that some participants were incorrectly placed in severity group.

Anderson and Catroppa (2007) conducted a study on memory outcome at 5 years after TBI in 70 children who were between the ages of 2 and 7 at the time of injury. The study found that children who sustained severe TBI performed more poorly than controls on spontaneous and delayed recall using the Wide Range Assessment of Memory and Learning (WRAML; Sheslow & Adams, 1990) Verbal Learning Test, a list-learning task. There was a degree of memory impairment in complex auditory-verbal memory that was evident at the test time, but was only present in those who had a severe TBI (Anderson & Catroppa, 2007). The research shows that there are impairments in various areas of verbal learning that are most significant in children who have sustained a severe traumatic brain injury.

Shum, Harris, and O’Gorman (2000) conducted a study on the effects of TBI on verbal and visual memory. Using three groups of participants (Early-Recovery, Late-Recovery, and a Control group), 42 adolescents and young adults were assessed using the Rey Auditory Verbal Learning Test (RAVLT; Rey, 1964) and the Shum Visual Learning Test (SVLT; Shum, O'Gorman, & Eadie, 1999). Individuals with severe TBI had impairments on the RAVLT, with the ability to learn and recall words being the most impaired. Children with TBI showed a slower rate of learning on tests of visual memory. The results of this study may be impacted by the extremely small size of the sample (N=14) and generalizability is limited to adolescents and young adults due to the age range of the sample.

In summary, after a traumatic brain injury, children with more severe injuries demonstrate impairments in their verbal memory on performance-based tasks (Anderson & Catroppa, 2007; Campbell et al., 2004). Research also found that after a period of time, verbal memory returns to normal. In this study, verbal memory will be studied as a function of working memory and the relationship to injury severity will be explored.

California Verbal Learning Test – Children. The California Verbal Learning Test - Children (CVLT-C: Delis, Kramer, Kaplan, & Ober, 1994) is a comprehensive measure of verbal learning. It measures aspects of how verbal learning occurs, as well as the amount of verbal material learned. Mottram and Donders (2006) conducted research to determine if there is a profile of verbal learning subtypes in children with TBI. This study used 175 children as participants, and four profile subtypes (clusters) were used. The subtypes were divided into Attention Span, Delayed Recall, Inaccurate Recall, and Learning Efficiency (Mottram & Donders, 2005, 2006). The study shows that children with TBI have similar patterns in memory and learning as children without TBI on the California Verbal Learning Test (CVLT-C) and none of the four clusters create a unique profile on the CVLT-C after a TBI. This study did not group participants based on severity and all children with traumatic brain injury were in one group.

Salorio et al. (2005) used a sample that consisted of 76 children with moderate and severe TBI. Using Donders' (1999) 5-factor model that includes the clusters listed in the previous study (Mottram & Donders, 2006) but separates Delayed Recall into Free Delayed Recall and Cued Delayed Recall, the study found that GCS was not predictive of CVLT-C performance for the four factors. For Learning Efficiency, Delayed Recall, and Inaccurate Recall, the volume of lesions in the frontal and temporal regions was predictive of outcome. The greater total number of brain lesions was predictive of worse performance on the CVLT-C variables.

Donders and Nesbit-Greene (2004) conducted a study on the demographic and neurological variables that could explain the variance on the CVLT-C and WISC-III performance following a traumatic brain injury. The study had a sample size of 100 children between the ages of 9 and 16. The study looked at the influence that ethnicity, gender, and socioeconomic status had on the CVLT-C and WISC-III, as well as the number of days in coma, diffuse lesions, and focal lesions. They concluded that longer length of coma was associated with worse performance on both tests, and girls performed better than boys. Speed of information processing showed a mediating effect between demographic and neurological variables and performance on the CVLT-C.

Prospective Memory

Prospective memory is the memory for future intentions that is executed at designated times or in response to cues. One study (Ward, Shum, McKinlay, Baker, & Wallace, 2007) compared children and adolescents with traumatic brain injury with noninjured children and adolescents to determine if puberty and the development of the prefrontal regions have an effect on the ability to respond to prospective cues. The study found that children and adolescents with traumatic brain injury responded to fewer prospective cues than children and adolescents without TBI. As the cognitive demand for the task increased, the response to the cues decreased, suggesting an inverse relationship.

In the study conducted by van Heugten et al. (2006) described previously, 31 children were evaluated on progress in their neuropsychological functioning several years after their injury, compared to normal functioning. Participants' memory was tested using the Rey Auditory Verbal Learning Test (RAVLT: Rey, 1964). The research found that after the TBI, memory was normally disturbed and very few children improved after a 3 year period and rehabilitation.

Working Memory

Working memory is defined as the brain's ability to monitor, process, and maintain task-relevant information and respond to immediate environmental demands (Baddeley & Logie, 1999). Working memory can also be defined as the brain's ability to retain information while processing or using that information to complete a task (Gioia et al., 2000). Mandalis and colleagues (2007) conducted research to determine if there is an association between working memory and new learning in children who sustained traumatic brain injury. They assessed 36 children with moderate and severe traumatic brain injuries between the ages of 6 and 16. These participants were compared to a control group of the same age range. This study used the definition of working memory (Baddeley & Logie, 1999) and the Working Memory model (Baddeley & Hitch, 1974; Baddeley, 2001) to determine if children with significant TBI have deficits in working memory, and if these deficits contribute to new learning difficulties. According to Baddeley (2001), working memory is comprised of two slave systems (phonological loop and visuospatial sketch pad), a central executive and an episodic buffer. The phonological loop is responsible for immediate registration and rehearsal of language-based information, and the visuospatial sketch pad for visuospatial information. The central executive system has four main functions: selective attention, divided attention, strategic retrieval of information from long term memory, and switching of attention. The episodic buffer provides a workspace for temporary storage of information and integrates the information from the slave systems and long term memory to create one unitary event. Mandalis et al. (2007) tested the phonological loop using the Forward Digit Span subtest on the WISC-III, and the central executive functioning using the Tower of London (TOL: Shallice, 1982), Controlled Oral Word Association Test (COWAT: Spreen & Strauss, 1998), and the Animal fluency test (Halperin et al., 1989). The study found that children who have sustained TBI had significantly poorer results on forward digit span and required more trials to complete the TOL, when compared with the control group. Children with TBI have lower phonological loop and central executive resources compared to controls, and these resources were taxed to a greater extent than the controls when learning new verbally-based material, when assessed using the RAVLT. The TBI group was able to utilize goal-directed behavior, but experienced difficulty when they needed to shift their goal plan and use multiple trials to solve the problem. The moderate-to-severe TBI group showed working memory difficulties on all tasks assessed, and these difficulties contributed to their verbal learning performance. These children also were less successful in accessing information from long-term memory on tasks of information retrieval. This study also found that working memory deficits may partially explain new learning dysfunction in children with TBI. With the impaired phonological loop system and central executive capacities reduced, initial encoding, a critical feature of new learning, is poor and leads to a reduced performance on learning, tasks of delayed recall and recognition. There are limitations to this study due to the relatively small sample size of 36 TBI participants; thus, the absence of comparison between moderate and severe TBI severity. This study uses both moderate and severe TBI to comprise the TBI group and uses a control group to enhance the validity of the findings (Mandalis, Kinsella, Ong, & Anderson, 2007).

Levin et al. (2002) found that older children around the age of 12 with severe TBI showed more difficulty on an n-back (Kirchner, 1958) task than children with mild TBI and children without TBI, and performance deteriorated as the memory load was increased and children began to have disinhibited responses. An n-back task requires the test-taker to constantly update information (Baron, 2004), and is commonly used as a working memory task. The task involves the manipulation of memory load and semantic or phonological target types; this study utilized matching letters based on meaning of the letter or on sound and rhyming. This study also found that as age increased there was an effect on improvements in phonological working memory and inhibition.

Roncadin et al. (2004) studied the maintenance and load aspects of verbal working memory in 126 school-age children and adolescents with TBI at least one year after injury. Participants were divided into groups based on severity (mild, moderate, and severe), and given the Recognition Memory Test (Goldman, Fristoe, & Woodcock, 1974) that examines judgments about prior occurrences of target words. Their results indicate that severe traumatic brain injury is associated with overall working memory impairment. Moderate TBI affects working memory to a lesser extent, and children with mild TBI were spared the effects on verbal working memory. Working memory was further divided into three components: task maintenance, sustained activation, and the ability to maintain and hold on to several items for a future response. Task maintenance was compromised after a severe TBI, and sustained activation was also deficient. At several years post-injury, children with moderate and severe TBI had significant and persistent working memory problems when holding verbal information.

However, this study did not utilize a control group and used a test that measures more verbal and visual memory than working memory, and describes the findings as working memory.

As previously reported, Anderson and Catroppa (2007) studied memory outcome five years after a mild, moderate, or severe traumatic brain injury sustained in childhood. Participants were given the Digits Forward subtest on the WISC-III (Wechsler, 1991), and Block Span (Milner, 1971) as tests of immediate memory; and Digits Backward (WISC-III: Wechsler, 1991) as a test of working memory. There was an absence of group differences between all groups on the tests of immediate memory and working memory performance. The research found that working memory was not significantly predicted by the GCS. This study was conducted at 5 years post-injury and used only the Digits Backward as a test of working memory (Anderson & Catroppa, 2007).

Chapman et al. (2006) researched the relationship between immediate memory and higher level working memory abilities with discourse gist production in children who had sustained a traumatic brain injury. Participants were between the ages of 8 and 14 and grouped into mild TBI and severe TBI based on their Glasgow Coma Scale. This study also utilized a control group comprised of 24 typically developing children. This study found that children with a severe TBI have an impaired ability to produce gist-based texts on a novel measure of summarization, and even children who sustained a mild TBI may be vulnerable.

They concluded that children who suffer a TBI will remain at risk for developing the necessary skills to select and retrieve information, manipulate it, and abstract the general meaning from discourse. They also discovered that immediate memory for discourse content was impaired, and the ability to produce a well-formed summary had a correlation with both immediate and working memory. Working memory was measured using the n-back task (Kirchner, 1958) and significant differences were found between all groups. The control group performed the highest and the children with severe TBI performed the lowest. Chapman et al. (2006) did not use participants with moderate TBI in the study, but did use a control group to determine the impairment of discourse gist.

Moran and Gillon (2005) also studied the relationship between working memory and language performance, and hypothesized that one method of looking at the relationship is to identify various factors that can constrain and facilitate working memory and watch the effects of manipulation on language behavior. Using six adolescents between the ages of 12 and 16 who had sustained a traumatic brain injury several years before the study and six age-matched control participants, a relationship between performance on a working memory span task (Tompkins, Bloise, Timko, & Baumgaertner, 1994) and performance on an inference comprehension task was found when individuals had to store the inference over a longer period of time. Possibly because of the small sample size, there was no significant difference between patients with or without a TBI with respect to working memory capacity.

In summary, the literature is inconsistent as to the effect that severity has on working memory after a traumatic brain injury. Anderson and Catroppa (2007) found, using Digits Backwards, a common measure of working memory at 5 years post injury, no group differences between traumatic brain injury groups or the control group and TBI groups. Using Digits Forward, Mandalis et al. (2007) found that children with severe traumatic brain injuries had significantly poorer results, when compared with the control group at 12 months after injury. Chapman et al. (2006) found significant differences between all groups on an *n*-back task, with children with severe TBI performing poorer than children with a mild TBI or the control group. Mandalis et al. (2007) also found new verbal learning and verbal working memory difficulties in children with severe TBI. Similarly, Roncadin et al. (2004) found that moderate and severe TBI have significant deficits in verbal working memory. Due to the literature inconsistencies on the effect severity has on measures of working memory, this study aims to further the knowledge and understand the role that severity plays on verbal working memory after TBI.

Rationale

Traumatic brain injury has been shown to have a significant impact on aspects of cognition, including executive functioning and working memory.

Working memory is defined as the brain's ability to retain information while processing or using that information to complete a task. This function is important because it is essential to complete mental activities such as arithmetic, follow complex instructions, or complete multistep tasks. When working memory is impaired, children will often have difficulty remembering numbers, names, or directions, or have trouble sustaining attention and switching tasks. While there is some literature to suggest long term difficulty with working memory in children who have sustained TBI, the literature is inconsistent on the extent to which working memory is affected by traumatic brain injury and whether different levels of severity of TBI differentially impact working memory.

Previous research has been conflicted to the degree that working memory is affected by traumatic brain injury (Anderson & Catroppa, 2007; Mandalis et al., 2007; Moran & Gillon, 2005) and it is unclear how children with moderate and severe traumatic brain injuries are impaired on measures of working memory. Traumatic brain injury has been shown to affect the level of working memory deficits in studies with large sample sizes (Chapman, et al., 2006; Mandalis, et al., 2007; Roncadin et al., 2004). One study demonstrated that children with a moderate TBI suffer working memory dysfunction to a lesser extent than children with a severe TBI, using a less common verbal memory test (Roncadin, et al., 2004). The current study utilized commonly used measures of working memory to verify the findings of the effects of severity on working memory functioning.

The current study examined the difference between groups determined by GCS Score, using moderate and severe groups, when employing multiple measures of working memory. A direct measure of working memory used in this study was the Working Memory Index from the WISC-IV. The CVLT-C Trial 1 was also used as a direct measure of verbal short-term memory. Working memory was measured indirectly by using the Working Memory Scale from the BRIEF, which is based upon parental reports of functioning. Specific variables included the Working Memory Index score from the Wechsler Intelligence Scale for Children – Fourth Edition, Trial 1 z-score from the California Verbal Learning Test for Children, and the Working Memory Scale T-score from the Behavior Rating Inventory of Executive Function. For this research, severity was the primary focus for predicting outcome in the pediatric population and was determined by the initial GCS score. It was important to determine how severity affects working memory to understand the impact of this domain has on a child’s daily functioning and to better guide parent education and child rehabilitation following TBI.

Chapter III

Method

Participants

Data for this study were collected from records at Children's Medical Center. The participants for this study were children who were admitted to Children's Medical Center Dallas pediatric intensive care unit for observation or treatment of a traumatic brain injury caused by blunt force who consented to participation in a neurobehavioral outcomes study following TBI through the Perot Family Center for Brain and Nerve Injuries. Traumatic brain injury must be the primary diagnosis and the severity level must be severe or moderate. The severity level was determined by the Glasgow Coma Scale, with severe being an initial GCS of 8 or less and moderate being a GCS of 9-12. The ages of participants were between 6 and 16 years old. Ethnicity and gender were not used to exclude participants. A penetrating head injury or non-accidental injury excluded a patient from the study. Records were reviewed only for patients whose parents signed consent for participation in the neurobehavioral study.

Participants in this study were recruited by the research team members as patients of Children's Medical Center Dallas. The identity of participants was known or was able to be ascertained by this study's investigator, limited research personnel and IRB members.

Instrumentation

The Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV: Wechsler, 2003) was given to children 6 and up as a part of the outcome study. The Working Memory Index was used for this study. This index includes the Digit Span and Letter Number Sequencing subtests. Digit Span is comprised of two parts: Digit Span Forward and Digit Span Backward. It requires a child to repeat the numbers in the same order as read by the examiner, or to repeat the numbers in reverse order as read by the examiner, respectively. The trials increase in number of digits to be remembered. Letter-Number Sequencing requires a child to hear a random sequence of numbers and letters and recall the information given while placing the numbers and letters in ascending order, with numbers being placed before letters. Each subtest has a mean (M) of 10 and a standard deviation (SD) of 3. The WMI produces a standard score with a mean of 100 and a SD of 15. The range is from 50 to 150. The WMI has an average internal consistency coefficient of .92, and a test-retest coefficient of .89.

The California Verbal Learning Test – Children's Version (CVLT-C: Delis, Kramer, Kaplan, & Ober, 1994) was used to test how verbal learning occurs and the amount of verbal material learned. The CVLT-C was given to children ages 6 to 16 years 11 months as a part of the outcome study. The current study used only the Trial 1 z-score. The CVLT-C has an internal consistency average of .88, an across-trial validity of .88, an across-semantic-category validity of .72, and an across-word validity of .81. Test-retest reliability, with a median interval of 28 days, ranges from .17 to .90 between the ages of 8 and 16 (Delis et al, 1994).

The Behavior Rating Inventory of Executive Functioning (BRIEF: Gioia, Isquith, Guy, & Kenworthy, 2000) was completed by parents and teacher as a part of the outcome study. Ratings from the parents of all children 6 and older will be used for the current study. The BRIEF has 2 main scales: Behavioral Regulation Index and Metacognition Index. Each contains specific subscales. The Working Memory Scale is a component of the Metacognition Index. This study used the Working Memory subscale as an indirect measure of working memory. The Working Memory scale produces a T-score with a mean of 50 and a SD of 10. A higher score on the Working Memory scale indicated more significant problems. The BRIEF has an internal consistency coefficient of .89 for parents, and .93 for teachers on the Working Memory Scale. There is an interrater reliability of .32 between parents and teachers, and a test-retest reliability of .81 for the parents and .87 for teachers.

Procedure

This study was approved by the Institutional Review Board of the University of Texas Southwestern Medical Center. This study was conducted retrospectively from data that have been previously collected. Participants who met inclusion criteria were assessed at 3, 6 and 12 months. Once the data were collected, they were input into the Brain and Nerve Injury Clinic database. For this study, the database was reviewed and the following variables were extracted: Working Memory Index score from the WISC-IV, Trial 1 z-score from the CVLT-C, Working Memory Scale T-score from the BRIEF, and the Glasgow Coma Scale score. Age, gender, ethnicity and mechanism of injury were also extracted to describe the sample. After the initial Glasgow Coma Scale score was extracted, the participants were divided into 2 groups for the purpose of this study: moderate and severe traumatic brain injury. At 6 months post-injury, participants were assessed using a battery of tests to assess their level of working memory. At 12 months post-injury, the participants were assessed with a similar battery of tests. This study used data collected from 6 to 12 months.

Design

Since children were assigned to a moderate or severe TBI group, by the GCS, a random assignment was not possible. As a result, this study had a quasi-experimental design. The participants were placed into two groups. The groups were defined by a score of 9-12 for moderate injury and 3-8 for severe injury on the Glasgow Coma Scale. The two levels of the independent variable was moderate or severe traumatic brain injury. Both groups received the same evaluation tools and were compared with respect to the working memory and verbal memory variables described above.

Hypotheses for the study are listed below. For Hypothesis 1, the independent variable was severity of injury: severe traumatic brain injury (a score of 3-8) and moderate traumatic brain injury (a score of 9-12). The dependent measures were the Working Memory Scale of the parent-report BRIEF (Gioia et al., 2000), Working Memory Index of the WISC-IV (Wechsler, 2003), and Trial 1 of the CVLT-C (Delis, Kramer, Kaplan, & Ober, 1994). For Hypothesis 2, the independent variable was also severity of injury and the dependent measure was the Working Memory Scale of the BRIEF. For Hypothesis 3, the independent variable was severity of injury and the dependent measure was the Working Memory Index of the WISC-IV. For Hypothesis 4, the independent variable was severity and the dependent measure was Trial 1 of the CVLT-C (Delis, Kramer, Kaplan, & Ober, 1994).

Hypotheses

1) There will be significant differences between the severity groups on measures of verbal working memory and verbal (short-term) memory.
2) Children with severe traumatic brain injury will show more impairment than children with moderate TBI on the BRIEF Working Memory Scale.
3) Children with severe traumatic brain injury will demonstrate more impairment than children with moderate TBI on the WISC-IV Working Memory Index.

4) Children with severe traumatic brain injury will demonstrate more impairment than children with moderate TBI on the CVLT-C Trial 1, a measure of short-term verbal memory.

Chapter IV

Results

Data Analyses

All analyses were performed using SPSS 17.0. Descriptive statistics, including means and standard deviations, for each measure are shown in Table 1. Scores were available for all participants on the *California Verbal Learning Test – Children's Edition* (n=23). Scores were missing for two participants for the *Behavior Rating Inventory of Executive Function* (n=21), and four participants for the *Wechsler Intelligence Scale for Children – Fourth Edition* (n=19). However, only 17 participants had all of the necessary scores and were used in the MANOVA for hypothesis-testing.

Analyses tested the hypotheses that (1) there would be significant differences between the severity groups on measures of verbal working memory and verbal short-term memory; (2) children with severe traumatic brain injury would show more impairment than children with moderate TBI on the BRIEF Working Memory Scale; (3) children with severe traumatic brain injury would show more impairment than children with moderate TBI on the WISC-IV Working Memory Index; and (4) children with severe traumatic brain injury would demonstrate more impairment than children with moderate TBI on the CVLT-C Trial 1. Each of these analyses of variance resulted in an F-value (MANOVA and ANOVAs) that represents the differences between severity groups. Statistical significance for these analyses of variance was determined based on a preset alpha level, α=.05. The dependent measures were defined as verbal memory and verbal working memory measures and the independent measure as the level of TBI severity.

Demographics and Descriptive Statistics

Twenty-three participants met criteria for the study and had data for the three tests of interest in this study. There was no evidence to suggest significant differences between the severity groups in terms of age at injury, $F(1,21) = 3.629$, $p = .071$. These findings suggest a non-significant trend for the age of injury, with severe injuries occurring in younger children. The mean age for the moderate TBI group was 9.91 years old, with a standard deviation of 2.66 years. The mean age for the severe TBI group was 7.92 years old, with a standard deviation of 2.35 years. As might be expected, increased severity was associated with a lower GCS score at admission. The moderate severity group had a mean GCS score of 10.82, with a standard deviation of 1.89. The severe group had a mean GCS score of 5.17, with a standard deviation of 1.75. Ethnicity was classified as Caucasian, Hispanic, African American, and Asian. Of the 23 participants, 15 were Caucasian (65%), 5 Hispanic (21.7%), 2 African American (8.7%), and 1 Asian (4.3%). There was no significant difference between groups in terms of ethnicity, when categorized as Caucasian and Non-Caucasian, $F(1,21) = 3.963$, $p = .061$. The mechanism of the injury was Motor Vehicle Accident (47.8%), Motor

Pedestrian Accident (21.7%), Falling Objects (8.7%), Falls (4.3%), Bicycle Accident (4.3%), and Other Mechanisms (8.7%).

Results of Hypothesis Testing

Working Memory Differences in Moderate and Severe Traumatic Brain Injury

The means and standard deviations for each measure are presented in Table 2. For the moderate TBI group, the mean T-score of the BRIEF Working Memory Scale was 62.00, with a standard deviation of 16.08. The mean of CVLT-C Trial 1, for this group, was a z-score of .36 with a standard deviation of 1.11. The mean standard score for the WISC-IV Working Memory Index was 97.43, with a standard deviation of 11.59, which falls in the Average range. For the severe TBI group, the mean of the Working Memory Scale was 63.10, with a standard deviation of 13.86. The mean for Trial 1 was -.50, with a standard deviation of 1.43. The mean for the WISC-IV Working Memory Index was 87.00, with a standard deviation of 20.01, which falls in the Low Average range. The means of the BRIEF Working Memory Scale, for both severity groups, were >60, which suggests clinical significance.

A multivariate analysis of variance (MANOVA) was used to examine the first hypothesis, which predicted that there would be a significant difference between moderate and severe traumatic brain injury on a combination of measures of working memory tested from 6 to 12 months post-injury. Moderate and severe TBI was the independent variable, while the BRIEF Working Memory

Scale T-score, CVLT-C Trial 1 z-score, and WISC-IV Working Memory Index standard score were the dependent variables. There was no significant multivariate main effect for severity on combined measures of working memory, $F(3,13) = .72300$, $p=.556$. Wilk's $\lambda = .85701$, $p = .556$. Thus, Hypothesis 1 was not supported.

Differences on BRIEF Working Memory Scale

There were 9 participants in the moderate group and 12 participants in the severe group for this analysis. The mean T-score of the moderate TBI group was 62.89, with a standard deviation of 14.36. The mean T-score for the severe TBI group was 62.50, with a standard deviation of 12.72. The means and standard deviations are also presented in Table 3.

An analysis of variance (ANOVA) was used to examine the second hypothesis, which predicted that children with severe traumatic brain injury would show more impairment than children with a moderate TBI on the BRIEF Working Memory Scale tested between 6 and 12 months. Moderate and severe TBI was the independent variable, while the BRIEF Working Memory Scale T-score was the dependent variable. While the means for both the moderate and severe TBI groups fall in the clinically significant range, suggesting that the groups are experiencing difficulty in this domain, there was no significant difference between moderate and severe TBI, $F(1,19) = .012$, $p = .915$, on the BRIEF Working Memory Scale. Hypothesis 2 was not supported.

Differences on WISC-IV Working Memory Index

The moderate TBI group had 9 participants and had a mean standard score of 96.22 on the WMI, with a standard deviation of 14.72, which falls in the Average range. The severe TBI group had 10 participants and a mean standard score of 87.00 on the WMI, with a standard deviation of 20.01, which falls in the Low Average range. The means and standard deviations are also presented in Table 3.

An analysis of variance (ANOVA) was conducted to examine the third hypothesis, which predicted that children with severe traumatic brain injury would exhibit greater impairment than children with moderate TBI on the WISC-IV Working Memory Index when tested between 6 and 12 months. Moderate and severe TBI was the independent variable, while the WISC-IV Working Memory Index Standard Score was the dependent variable. There was no significant difference between moderate and severe TBI, $F(1,17) = 1.284$, $p = .273$. Hypothesis 3 was not supported.

Due to the small sample size and lack of significant differences, additional analyses were conducted to determine if working memory could be further examined by looking at the WISC-IV Working Memory Index component parts. The component subtests of the WISC-IV Working Memory Index include Digit Span and Letter-Number Sequencing. Participants who did not have a WISC-IV Working Memory Index score had at least one of the component subtests. Digit

Span was administered to 22 participants and Letter-Number Sequencing to 19 participants. Means and standard deviations are presented in Table 3.

The mean scaled score for the moderate TBI group on Letter-Number Sequencing (LNS) was 8.89, with a standard deviation of 3.30. The mean scaled score for the severe TBI group on LNS was 7.60, with a standard deviation of 4.14. Overall the moderate group scored in the Average range while the severe group scored in the Low Average range. No significant difference was found between groups for Letter-Number Sequencing, $F(1,17) = .554$, $p = .467$ suggesting that, even though the moderate group performed in the clinically average range while the severe group performed in the clinically low average range, the two groups do not significantly differ on this variable.

The mean scaled score for the moderate TBI group on the Digit Span (DS) subtest was 9.45, with a standard deviation of 2.50. The mean scaled score for the severe TBI group on DS was 7.55, with a standard deviation of 3.64. The moderate group mean fell in the Average range for Digit Span, while the severe group performed in the Low Average range. Even though the groups performed in different clinical ranges, ANOVA did not reveal a statistically significant difference on Digit Span, $F(1,20) = 2.051$, $p = .168$, suggesting that children with severe traumatic brain injury do not necessarily show more difficulties on Digit Span compared to children with moderate TBI.

Additional analyses of variance (ANOVA) were conducted to determine if an individual component of the Digit Span subtest was more susceptible after a TBI. The components of Digit Span are Digits Forward and Digits Backwards. These components were administered to 22 participants. For the Digits Forward component, the mean scaled score for the moderate TBI group was 8.00, with a standard deviation of 2.05. This score was in the Average range. The mean of the severe TBI group was 6.64, with a standard deviation of 2.77. This mean score falls in the Low Average range. Means and standard deviations are also summarized in Table 3. Results of ANOVA indicated that no significant difference existed between the moderate and severe TBI groups for Digits Forward, $F(1,20) = 1.725$, $p = .204$.

The mean of the Digits Backwards component of Digit Span for the moderate group was 6.91, with a standard deviation of 2.77. The mean for the severe group was 5.09, with a standard deviation of 2.55. Again, the moderate TBI group performed in a higher clinical range compared to the lower performing severe group. Specifically, the moderate TBI group performed in the Low Average range while the severe group performed in the Borderline range. However, ANOVA revealed that no statistically significant difference existed for Digits Backwards, $F(1,20) = 2.564$, $p = .125$.

Differences on CVLT-C Trial 1

An analysis of variance (ANOVA) was used to examine the fourth hypothesis, which predicted that children with severe traumatic brain injury would show more impairment than children with moderate TBI on the CVLT-C Trial 1. This test was administered to 23 participants. The mean and standard deviations are summarized in Table 3. The mean z-score for the moderate TBI group was .23, with a standard deviation of 1.10, which was in the Average range. The mean z-score for the severe TBI group was -.75, with a standard deviation of 1.42, which was in the Low Average range. While there was no statistically significant difference between moderate and severe TBI, $F(1,21) = 3.343$, $p = .082$, a non-significant trend emerged with children who had more severe injuries showing more deficits than children who had moderate injuries.

Chapter V

Discussion

This study aimed to determine the effect that severity of traumatic brain injury has on measures of working memory 6 to 12 months after injury. It was anticipated that as the severity of the injury increased, the ability to perform verbal working memory and verbal short-term memory tasks would be impaired. In contrast to what was hypothesized, there were no significant differences between groups on multiple common measures of verbal working memory and verbal short-term memory. However, this study is in agreement with some previously reviewed literature (Anderson & Catroppa, 2007; Moran & Gillon, 2005) that found no statistically significant group differences between children with moderate and severe TBI on measures of working memory performance. There was one non-significant trend on Trial 1 of the CVLT-C, leaving open the possibility that differences may appear if limitations such as small sample size, a limitation that is common in TBI research, could be adequately addressed.

Injury Severity Group Comparisons

The prediction that traumatic brain injury severity would be related to significant differences on measures of working memory was not supported by the findings, with the moderate and severe groups not demonstrating statistically significant differences on composite measures of working memory including the BRIEF Working Memory Scale, WISC-IV Working Memory Index, and CVLT-C

Trial 1. Thus, as a composite, the overall aggregate of variables was not able to distinguish between the moderate and severe groups. However, clinically, such a composite is not typically used, so it is of interest to examine each of the individual measures of verbal memory used in this study.

The anticipated relationship between level of TBI severity and impairment on the BRIEF Working Memory Scale was not found, as children with moderate and severe TBI demonstrated statistically similar mean parent ratings. Although there were no significant differences between severity groups, it is noteworthy that both groups had mean scores that are considered “clinically significant” compared to the general population, suggesting that parents are observing working memory deficits in these children with TBI. This suggests that children who experience a moderate or severe TBI have difficulties with everyday tasks of working memory, at least as observed by their parents.

These results may indicate that there is no difference between the two groups as measured on the BRIEF Working Memory Scale. While this is a similar finding to the study conducted by Mangeot et al. (2002) in which the BRIEF Working Memory Scale did not show significant group differences between children with moderate and severe TBI, the study found that only the severe TBI group was in the clinical range. Sesma et al. (2008) found that none of the severity groups had clinically significant scores on the Working Memory Scale. While there may not be a significant difference between groups, this area would benefit from further research to determine where the impairment lies. The current study and past literature are conflicting as to how everyday working memory is affected by moderate and severe traumatic brain injuries.

The scores on the BRIEF Working Memory Scale may be elevated for both severity levels due to parents noticing more everyday impairments that may not be tested in more direct measures. Vriezen and Pigott (2002) found a low correlation between neuropsychological testing of executive functioning and the BRIEF parent rating as the scores on the parent rating were higher than those of the neuropsychological assessments. While the Vriezen and Pigott study (2002) did not look directly at functional measures of working memory, together with the present study these findings can help understand that parents of children with moderate or severe TBI sometimes view their children with TBI as experiencing difficulty with working memory, even though the parent ratings do not distinguish between the two severities in terms of different levels of working memory dysfunction. Parents of children who have sustained traumatic brain injury may be more sensitive to working memory deficits that other neuropsychological tests are not sensitive to. Although the BRIEF Working Memory Scale may be more sensitive than the other scales, the BRIEF may not be sensitive enough within the clinical range to be sensitive to differential deficits between these two groups. In other words, it may be that a more sensitive rating measure may detect differences according to severity that the BRIEF does not, an issue that could potentially be addressed in future studies.

The predicted relationship between TBI severity and impairment on the WISC-IV Working Memory Index was not found. The means for the Working Memory Index are close to 1 standard deviation apart, with the severe group having a lower score. When a clinical interpretation is applied in terms of assigning range descriptors, the moderate group performed in the Average range, while the severe group performed overall in the Low Average range, suggesting a slightly greater level of functional difficulty with working memory for children with severe TBI as compared to children with moderate TBI. Again, while it is reiterated that no statistically significant difference was detected between the moderate and severe groups, the current findings may have clinical relevance to help medical professionals know how the severity of the injury can affect children in cognitive rehabilitation settings. Babikian and Asarnow (2009) conducted a meta-analytic review of previous literature and found negligible differences between children with moderate TBI and children with severe TBI on measures of working memory, including the Working Memory Index. However, this analysis did not separate the subtests that contribute to the Working Memory Index, but did use WMI as a part of the working memory composite. The analysis also found that significant differences emerged between onset and 24 months after injury for the severe group.

The results from the current study suggest that children who sustain a moderate traumatic brain injury demonstrate an ability to perform the WISC-IV working memory tasks on a level similar to the normal population of children. Alternatively, children with a severe traumatic brain injury may demonstrate statistically similar performances on the WISC-IV working memory tasks compared to children with moderate TBI, but may find the ability to hold information, manipulate that information, and use it at a later time to complete a task more difficult than children with a moderate brain injury and the general population of children. Although research has not found group differences on the Working Memory Index, the differences in clinical ranges for the group means suggest that further research may be warranted to determine the impact of these range differences.

This study was the first to look at the specific components of the WISC-IV Working Memory Index as they related to working memory. When the WISC-IV Working Memory Index was further separated into its component subtests (Letter-Number Sequencing and Digit Span), there were no significant differences between groups on either subtest. As was the case for several of the other variables directly testing working memory functions, the moderate and severe group means were each in a different clinical range. The moderate TBI group had a mean scaled score in the Average range on Letter-Number Sequencing. The severe group had a mean scaled score in the Low Average range on LNS, suggesting that these children may perform at a slightly lower level than the norm during the same period of time.

Injury severity does not appear to associate with performance on Digit Span for the two groups. Similar to Letter-Number Sequencing, the severity groups were in different clinical ranges though not statistically significantly different from one another. The moderate TBI group had a mean scaled score in the Average range suggesting that this group did not perform in a range that would typically raise clinical concern. The severe TBI group was again in the Low Average range for mean scaled score, suggesting this group may experience clinically relevant difficulty in this domain even though there is not a statistically significant difference between the moderate and severe TBI groups.

In sum, results suggest that children who sustain a moderate traumatic brain injury may be able to perform common tests of working memory on a level that is not suggestive of clinically significant difficulty. Children with a severe traumatic brain injury may be able to perform statistically similarly to moderately injured peers, yet may be at greater risk for struggling, from a clinical perspective, in areas that require retaining information while processing or using that information to complete a task.

In order to further investigate that the severe TBI group may perform slightly worse, though not statistically significantly so, on Digit Span compared to their moderately injured counterparts, Digit Span was separated into its individual components (Digits Forward and Digits Backward). Similar to other group comparisons on measures of working memory, no statistically significant differences were found between severity groups on Digits Forward or Digits Backwards. However, children who sustained a moderate traumatic brain injury performed in the average range, while those that sustained a severe TBI performed Digits Forward in the Low Average range. This is consistent with performances on other working memory measures, although Digits Forward is used as a test of short-term memory and not working memory. Anderson and Catroppa (2005) discovered no significant group differences at 24 months after injury on Digits Forward, but found that the severe TBI group showed the greatest improvement in performance over time. In contrast, Mandalis et al. (2007) found that children with severe traumatic brain injuries performed more poorly on Digits Forward than children without injury. The findings of the current study are consistent with findings from the Mandalis et al. (2007) study, but more research is needed in this area to conclusively address this issue. The findings from the current study indicate that children who sustained a severe traumatic brain injury may be more at risk for difficulties recalling strings of numbers.

The current study did not find differences between groups on Digits Backwards, which research has often used as a measure of working memory. Children with moderate brain injuries were not statistically better able to complete sets of reversing numbers compared to their severely injured counterparts.

However, both groups showed clinically significant deficits as measured on Digits Backwards with the moderate group performing in the Low Average range and the severe group performing in the Borderline range. While no group differences were found, the scores for both severity groups indicate there may be a problem in working memory after TBI. Anderson and Catroppa (2007) also found that there were no group differences between severity groups on Digits Backwards. However, their study was conducted at 5 years after injury, and the lack of significant results may indicate that working memory improves over time. Limitations of the current study leave open the possibility that working memory as measured by Digits Backward may be affected by severity, but factors including small sample size may hinder the identification of real differences between the moderate and severe groups. Another possible explanation for the lack of group differences may be the sensitivity of the measure to severity. In other words, this particular method of measuring working memory may not be sensitive to determine statistically significant differences between the two groups.

The anticipated relationship between level of TBI severity and verbal short-term memory performance on the CVLT-C was not found. Again while there were not statistically significant differences, each group mean fell in a different range of clinical interpretation. Specifically, the severe TBI group had a mean score that was in the Low Average range while the moderate TBI group had a mean score that was in the Average range. A mild non-significant trend emerged as the difference between means appeared to approach statistical significance, with children with more severe injuries showing more difficulties with a list-learning task than children with moderate injuries. More research in this area with a larger sample size may shed light on this trend further.

Verbal short-term memory may be relatively impervious to the effects of traumatic brain injury, but children with more severe brain injuries may find difficulty in using immediate memory to recall lists of words read to them. One possible explanation of the findings may be a deficit in the attention domain after injury. Catroppa et al. (2006) found that children with TBI have difficulties with sustained attention in timed conditions. This inability to sustain attention may cause a child with a severe TBI to lose track of the list of words faster and reach a maximum frustration level sooner. Campbell et al. (2004) found that children who sustain a TBI may have more difficulties summarizing lists to put into later use. This may cause children with traumatic brain injury to be unable to categorize the list of words into a form that is more easily remembered. The 15-word list may also not be sensitive enough to the deficits in short-term verbal memory that may occur after a child sustains a traumatic brain injury.

Implications of the Study

This study aimed to determine the effects of injury severity on working memory during an interval 6 to 12 months after TBI in children. There were no significant differences between children with moderate traumatic brain injury and children with severe traumatic injury on all measures of verbal working memory and verbal short-term memory used. A clinical trend emerged, suggesting that children with severe brain injuries may experience more difficulties with working memory and have a degree of impairment retaining information while processing or using the given information. Even though statistically significant differences were not detected, this study found that the children with severe TBI performed in the Low Average range or lower on all tasks. The moderate group’s mean performance level generally fell in the Average range on most tasks. Both groups were impaired on the BRIEF Working Memory Scale and Digits Backwards from the WISC-IV. Children with moderate and severe TBI may be doing poorly in everyday life, though it may be that current measurement methods are not entirely sensitive to these differences.

The current study’s findings suggest that working memory may not be intact after traumatic brain injury and standardized evaluations of cognitive functioning in the TBI population may not properly demonstrate impairments. Although there were no significant differences between children who sustained a moderate or severe TBI, this function could potentially be at risk in these children. More specifically, children who sustain a severe traumatic brain injury are at risk for working memory problems. These difficulties may manifest as problems with remembering names, strings of numbers, or directions. Children who have working memory problems may also struggle with mental math tasks, following complex instructions, or completed multistep activities.

These results suggest that an investigation of working memory after traumatic brain injury is an important area of research that merits future studies. Future research in this area may give medical professionals more information about the impact of the severity of the traumatic brain injury and its effects on a child's outcome. The current study findings suggest that working memory and verbal short-term memory are a functional area that appears vulnerable to the effects of traumatic brain injury. Working memory remains an important area for clinical attention. Research may also provide medical professionals with the ability to give a more accurate prognosis about working memory to families of children who have sustained a traumatic brain injury. In knowing the prognosis, the professional or treatment team may be in a better position to recommend targeted rehabilitation to assist the child in recovery.

Limitations and Future Directions

The present study is an investigation into verbal working memory and how it is affected by the severity of a pediatric traumatic brain injury. However, the conclusions are weakened by the extremely small sample size of participants who had been given the necessary tests, and may not be fully representative of the population of children with moderate or severe TBI.

This study also did not use a control group or children with mild traumatic brain injuries due to their exclusion from the study. This limitation may also lead to a decrease in generalizability due to lack of inclusion of a more rounded population sample. The use of only the Glasgow Coma Scale to determine TBI severity may have led to participants being classified into the wrong severity group, since other factors such as length of time on a ventilator or pupil reactivity also have relevance as measures of severity.

The clinical instruments may have also presented a limitation to this study. The instruments have been tested and validated as good measures of working memory but may not have the level of sensitivity that is necessary to detect differences between moderate and severe traumatic brain injuries. These working memory measures can continue to be explored, researched, and refined to make sure that assessment strategies are as valid and sensitive as possible.

Future studies could improve upon the present study in a number of ways. A larger sample size would be necessary to determine if significance differences between groups are possible. A larger sample size would allow for more of the population to be included and extend generalizability. This could also be conducted utilizing a control group or including mild traumatic brain injuries. Including these groups would allow for a larger population and would help to determine if there are differences along the severity continuum. Furthermore, while the study had a large age range, many participants sustained the injury at an age younger than the ages for which the current measures were appropriate. Several of these participants were given measures that were more compatible with younger ages, and given the current measures at a later follow-up. Future research may endeavor to include the measures appropriate for younger children to determine the effect of traumatic brain injury severity on a wider age range of children.

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Table 1

Demographics and Injury Characteristics. N = 23

	Moderate N = 11	Severe N = 12
Age at injury (years), *M* (SD)	9.91 (2.66)	7.92 (2.35)
GCS (initial), *M* (SD)	10.82 (1.89)	5.17 (1.75)
Number of Males *n* (%)	8 (72.72)	8 (66.66)
Number of Females *n* (%)	3 (27.27)	4 (33.33)
Number of Caucasians *n* (%)	5 (45.45)	10 (83.33)
Number of Hispanics *n* (%)	3 (27.27)	2 (16.67)
Number of African Americans *n* (%)	2 (18.18)	0 (0.00)
Number of Asian Americans *n* (%)	1 (9.09)	0 (0.00)
Time Since Injury (months), *M* (SD)	9.82 (3.03)	10 (2.95)

M = Mean, SD = Standard Deviation, *n* = Frequency.

Table 2

Means and Standard Deviations for Neuropsychological Variables. *N* = 17

	Moderate		Severe	
	M	SD	M	SD
BRIEF Working Memory Scale (T-score)	62.00	16.08	63.10	13.86
WISC-IV WMI (Standard Score)	97.42	11.58	87.00	20.00
CVLT-C Trial 1 (z-score)	.35	1.10	-.50	1.43

M =Mean, SD= Standard Deviation

Table 3

Means and Standard Deviations for Severity Groups

	Moderate	Severe	F-value	p - value
BRIEF, *n* = 21	62.89 (14.35) *n* = 9	62.25 (12.72) *n* = 12	.012	.915
WMI, *n* = 19	96.22 (14.72) *n* = 9	87.00 (20.01) *n* = 10	1.284	.273
Digit Span, *n* = 22	9.45 (2.50) *n* = 10	7.55 (3.64) *n* = 12	2.051	.168
Digits Forward, *n* = 22	8.00 (2.05) *n* = 10	6.64 (2.77) *n* = 12	1.725	.204
Digits Backwards, *n* = 22	6.91 (2.77) *n* = 10	5.09 (2.55) *n* = 12	2.564	.125
Letter-Number Sequencing, *n* = 19	8.89 (3.30) *n* = 9	7.60 (4.14) *n* = 10	.554	.467
CVLT-C Trial 1, *n* = 23	0.23 (1.10) *n* = 11	-0.75 (1.42) *n* = 12	3.343	.082