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Parsing neurocognitive heterogeneity in pediatric traumatic brain injury

Brian D Leany
University of Nevada, Las Vegas

PARSING NEUROCOGNITIVE HETEROGENEITY IN

PEDIATRIC TRAUMATIC BRAIN INJURY

by

Brian D. Leany

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Brian D. Leany, B.A.

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ABSTRACT

Parsing Neurocognitive Heterogeneity in Pediatric Traumatic Brain Injury

by

Brian Leany, B.A.

Dr. Daniel Allen, Examination Committee Chair
Associate Professor of Psychology
University of Nevada, Las Vegas

Traumatic brain injuries (TBI) occur quite frequently in children and adolescents. One difficulty in understanding and treating TBI lies in the heterogeneous nature of its acquisition and mechanism of injury, and the resulting neurocognitive impairment. While there are instruments that exist to identify such impairment, they typically are divided into very broad domains of academic performance. Tests such as the Wechsler Intelligence Scale for Children (WISC) and the Woodcock Johnson are helpful in identifying impairment within the realm of academic aptitude, but have thus far not provided specific enough information as to the impairment of the underlying neurocognitive process that may be causing the degraded performance. In recent years, however, there has been an increase in tests specifically to assess neurocognitive functioning in children. One such test, the Test of Memory and Learning (Reynolds & Bigler, 1994), includes both nonverbal and verbal components, similar to the WISC, as well as indices of performance that measure broader underlying neurocognitive processes such as memory, learning, and attention/concentration factors. The purpose of the current study was to investigate the heterogeneity in neurocognitive function demonstrated by children who have sustained a TBI. Understanding the profiles of neurocognitive impairment that occur in child TBI may assist in predicting outcomes and treatment planning. From a theoretical perspective, patterns of performance on neuropsychological tests may provide unique insights into the type of injury sustained and the brain structures that are most susceptible to injury. In the present investigation, heterogeneity in neurocognitive function was investigated using cluster analysis of neuropsychological domains assessed by the Test of Memory and Learning (TOMAL). A five-cluster solution for the TOMAL data was selected as the optimal cluster solution. It best exhibited differences in level and pattern of performance, as well as differences on important clinical and behavioral variables. Empirical support for the identification of clusters based upon TOMAL scores, Intelligence scores (IQ) and behaviors reported on the Behavior Assessment System for Children (BASC) further supported the selected cluster solution, and should assist clinicians in providing both a more informed prognosis and a more prescriptive treatment intervention.

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CHAPTER 1

INTRODUCTION

Traumatic brain injuries (TBI) occur quite frequently in children and adolescents. In 2004, the CDC reported over 1 million incidents of Traumatic Brain Injury, with the majority of these cases occurring as a result of a motor vehicle accident or an unintentional fall (CDC, 2004). Of these injures, a little over 20 percent were hospitalized and 5 percent resulted in death. This report demonstrated that the incidence of pediatric TBI is still occurring at a substantial rate. In fact, TBI is the leading cause of death from unintentional injuries in children age 0-14 (Langlois, Brown, & Thomas, 2004). The fact that these TBI's are occurring during critical periods of brain development should not be overlooked. Research has demonstrated an inverse linear relationship between age of onset of TBI and the level of neurocognitive impairment, so that those who are impaired earlier in life have more severe impairment. This relationship lasts into adulthood for these individuals. It has been posited that the younger a child is the less likely they are to have a solid foundation of cognitive skill-sets upon which to fall back on after sustaining a TBI (Anderson, 2000).

One difficulty in understanding and treating TBI lies in the heterogeneous nature of its acquisition and mechanism of injury. To better understand this heterogeneity and the potential prognostic and treatment implications we need to examine the ways in which we classify them in practice. TBI has been classified in a number of ways. The first such classification is the distinction made between open versus closed head injuries. They can further be classified as to hemispheric differences. While these classifications allow for more effective communication regarding the nature of the injury, they do not necessarily provide any indication as to the severity of injury, nor the prognosis. It would seem to some that an open head injury should be considered more severe than a closed head injury. However, this is not the case. While an open head injury does make an individual more susceptible to infection, it also allows for the release of pressure which could otherwise cause more damage than the initial trauma itself. In fact, in cases of severe head injury it has been suggested that Intracranial Pressure (ICP) be reduced through a surgical opening of the skull (Maas, et al., 1997). Conversely, this does not mean that a closed head injury has a worse prognosis. Besides the initial acute symptoms of TBI, such as coma or disorientation, there are often more chronic symptoms of neurocognitive and behavioral impairment. These neurocognitive impairments can consist of a broad range of presenting symptoms. While the most commonly reported impairments lie in the broader realm of attention, many studies have reported finding significant impairment in the domains of language and memory.

While there are instruments which exist to identify such impairment, they typically are broken down into very broad domains of academic performance. Tests such as the Wechsler Intelligence Scale for Children (WISC) and the Woodcock Johnson are helpful in identifying impairment within the realm of academic aptitude. However, they have thus far not provided specific enough information as to the impairment of the underlying neurocognitive process that may be causing the degraded performance. In recent years however, there has been an increase in tests specifically to assess neurocognitive functioning in children.

One such test, the Test of Memory and Learning (Reynolds & Bigler, 1994), includes both nonverbal and verbal components, similar to the WISC, as well as indices of performance that measure broader underlying neurocognitive processes such as memory, learning, and attention/concentration factors. An understanding of an individual's performance on these processes, which are thought to underlie the more specific higher level cognitive functioning, may better assist the clinician in making treatment recommendations and prognostic impressions, as well as provide insights into how TBI effects specific higher order neurocognitive processes.

These observations have lead some to suggest that a combination of neurological signs (e.g. length of coma), types of injury (open vs. closed head injury), and neuropsychological deficits may provide a better indicator of injury severity than any of these variables used in isolation (Reitan & Wolfson, 1993, Bigler & Clement, 1997).

Based on these considerations, the purpose of the current study is to investigate heterogeneity in neurocognitive function in children who have sustained a TBI. Such work has both clinical and theoretical implications. From a clinical perspective, understanding the profiles of impairment that occur in child TBI may assist in predicting outcomes and treatment planning. From a theoretical perspective, patterns of performance on neuropsychological tests may provide unique insights into the type of injury sustained and the brain structures that are most susceptible to injury. In the present investigation, heterogeneity in neurocognitive function will be investigated using cluster analysis of neuropsychological domains assessed by the TOMAL. It is anticipated that the TOMAL clusters, if valid, will exhibit differences in level of performance and possibly pattern of performance, as well as differences on important clinical and behavioral variables. Empirical support for the identification of clusters based upon TOMAL scores and behaviors reported on the Behavior Assessment System for Children (BASC; Reynolds, & Kamphaus, 1992) should therefore lend itself to a more informed prescriptive treatment and a more accurate prognosis, as well as an understanding of those brain structures sensitive to TBI.

CHAPTER 2

LITERATURE REVIEW

The following literature review will address areas relevant to the current proposal. These areas will include a description of traumatic brain injury, a description of current memory models for children, the assessment of Neurocognitive functioning in children, behavioral deficits that occur as a result of TBI, and cluster analysis.

Traumatic Brain Injury

TBI is a primary cause of neurological injury in the United States. The Centers for Disease Control and Prevention (CDC, 2004) estimate that each year 1.4 million people in the United States sustain a TBI, of which approximately 50,000 to 55,000 die. It is further estimated that 80,000 to 90,000 people will suffer a long-term or lifelong disability due to TBI (CDC, 2004). The leading causes of TBI are falls, motor vehicle accidents, and assaults (including child abuse). Motor vehicle accidents are the major cause of TBI in people under 75 years of age. For people 75 years and older falls cause the majority of TBI cases. These statistics provide information on the magnitude and relevancy of research in this area.

Most traumatic brain injuries are a result of a blow to the head that either directly injures the cerebellum or indirectly causes injuries through a sudden deceleration of the brain resulting in the brain contacting the skull, which protects it (Larrabee, 2004). The result is typically an alteration in consciousness and often times persisting neurobehavioral deficits.

Classification of Traumatic Brain Injury

In order to better understand the heterogeneity of TBI a need for a classification system is quite apparent. The primary classification of TBI has been based on the resulting physical nature of the injury itself. This classification is one of the easiest to make because it is a description of the wound being either open or closed. In open head injuries, the skull is fractured or damaged but in closed head injuries the skull integrity is maintained. Research indicates that there is no clear, consistent system for classifying the severity of injury for TBI (Bigler & Clement, 1997). However, a closed head injury is typically the most severe form of injury due to the potential build-up of pressure caused by internal swelling and bleeding. A penetrating head wound may also be severe, but can release pressure, which can reduce brain damage through the displacement of healthy cerebral tissue. However, it can also result in contact with the cerebral tissue, which would be more severe than if no contact was made depending on the extent of contact with the neural tissue, resulting damage to the tissue, and the possibility of infection.

Several attempts have also been made to systematically classify the severity of TBI. One such system has been proposed by Jenette and Teasdale (1981), Becker, Grossman, McLaurin, and Caveness (1979), and Coxe and Grubb (1978) and suggests that the injuries can be classified as mild, moderate, severe and profound. This system uses a variety of behavioral and neurological signs to classify severity of injury.

Mild TBI: results in a relatively brief alteration in the level of consciousness, which is 30 minutes to one hour in duration (Larrabee, 2004). During this time-period patients may seem slightly confused and disoriented, and are often referred to as concussions by physicians (Bigler & Clement, 1997). Problems may arise during the period immediately following the insult, which may last weeks. The fact that the symptomology has such a long duration and new information regarding the underlying damage during this period has directed more attention to this period after the initial injury (Reitan & Wolfson, 1993; Hannay, 2004).

Moderate TBI: Symptoms of moderate TBI will have all the same symptoms of Mild-TBI, but in this state there is an alteration in the level of consciousness that lasts longer than an hour or the person experiences focal neurological deficits. Moderate TBI may also include a headache that progresses in intensity and/or continues with no sign of relief, dilation of one or both pupils of the eyes, persistent vomiting or nausea, convulsions or seizures, an inability to awaken from sleep, slurred speech, weakness or numbness in the arms or legs, loss of coordination, or increasing levels of confusion. Nearly ¼ of all patients suffering from contusions and half of those who have suffered penetrating head injuries will develop seizures. These seizures can last as long as one week. Severe TBI: has similar symptoms to those already described, but also results in the loss of comprehension and comprehensible expression. The resulting state is often a coma. Profound TBI typically results in an unconscious state immediately after the TBI and typically results in death.

The Glasgow Coma Scale (GCS) (Teasdale & Jennet, 1974) has also been used to classify TBI. It is commonly used for assessing the severity of head trauma while the person is still in the acute posttraumatic state. GCS scores range between 3 and 15, with 3 suggesting severe impairment, and 15 being considered a baseline functional state. It is composed of three areas: Best Eye Response (Score 1-4), Best Verbal Response (Score 1-5), Best Motor Response (Score 1-6). The GCS's scaling system provides objectivity, reproducibility, and simplicity. When the GCS is properly used, the degree of inter-rater reliability is high. Subsequently, a change in the GCS from one assessment to the next is not only reliable, but further indicates a significant change in level of consciousness. Neurobehavioral deficit severity is generally categorized by GCS scores into mild (13-15), moderate (9-12), and severe (3-8), with scores of 8 or less being generally indicative of a comatose state (Teasdale & Jennet, 1974; Jennett & Teasdale, 1981; Lezak, Howieson, & Loring, 2004).

Some investigators have also utilized posttraumatic amnesia (PTA) to assess the severity of injury. PTA has been found to be well correlated with GCS scores (Levin, Benton, & Grossman, 1982). If PTA estimates are considered to begin at the point of injury it has been found that PTA will typically last four times the length of coma (Brooks, 1989). However, problems related to utilizing PTA as a determinate of severity create greater problems in practical application. For example, some researchers consider PTA to begin once the person is conscious (Bigler & Clement, 1997), while others initiate PTA estimates from the point of injury (Brooks, 1989). Other difficulties lie in determining when PTA has subsided and subjective reports from the person experiencing PTA. Additionally, medical professionals typically pay close attention to the length of time a person experiences a loss of consciousness (LOC), where longer levels of LOC tend to experience more outcomes that are negative. The use of PTA, LOC, GCS classification methods provide only gross, acute, and simple estimates of TBI severity.

Another way of evaluating the severity of brain damage is through neuroimaging and neurorencording technologies. Neuroimaging and neurorecording provide a way to evaluate the structural effects of the neural damage. Some of the more prominent forms are computerized tomography (CT) scans, magnetic resonance imaging (MRI), electroencephalogram (EEG), positive emission tomography (PET), and single photon emission computed tomography (SPECT). However, these methods are limited to evaluating structural and processing abnormalities and dysfunction. Thus, while neuroimaging procedures can provide precise information regarding structural abnormalities resulting from TBI, the neurobehavioral and Neurocognitive dysfunction is not directly detected or assessed with these techniques (Reitan & Wolfson, 1993; Hannay, 2004).

A precise evaluation of the neurocognitive effects of TBI is important for understanding the limitations and prognosis of individuals who are affected, and can be achieved through neuropsychological evaluation. To evaluate the broad spectrum of damage to the brain that can affect cognitive, emotional, sensory, and motor areas Reitan & Wolfson (1993) proposed a system of measurement. This system is based on evaluating interindividual differences (what levels of functioning are significantly below what is expected in the normal population) and intraindividual differences (patterns or signs of performance indicative of impairment) for determination of neuropsychological impairment. There are two general subsections within each of these two areas. Within interindividual differences there is the Level of Performance (LOP; scores low enough to be considered suggestive of impairment) and Pathognomonic Signs (PS; errors on tasks that are not typically missed by people in the normal population). In the intraindividual realm there is Pattern of Performance (POP; specific strengths and weaknesses that are uncharacteristic of typical neural functioning) and Right-Left Differences (R-L D; Dramatic differences in level of performance between measures typically indicative right hemisphere versus left hemisphere functioning). By assessing these four areas across essential domains of neuropsychological function Reitan and Wolfson, suggest that predictions can be made concerning preexisting conditions, recovery trends, and outcome of traumatic brain injured patients with some degree of certainty using the Halstead-Reitan Neuropsychological Test Battery (HRNB, Reitan & Wolfson, 1969). However, like many of the early tests that were originally developed for adults, the child version of the HRNB is a downward extension e.g. the adult version, an approach that has been criticized due to a number of methodological and conceptual problems. Fortunately, a number of Neurocognitive test batteries have been developed specifically for children to whom Reitan's approach can be applied. These approaches will be reviewed later, but first a brief description of current models of memory is provided.

Models of Memory: Cognitive Constructs and Neuroanatomical Structures

The study of human memory has long been an interest for the field of psychology from Miller's, 1956 study of the 7+/- 2 short-term memory store to the modern theories of memory storage, consolidation and recall, psychologists have studied the complex construct of memory in-depth.

The Atkinson and Shiffrin model of memory posits a three-component of memory (1969). This model suggests that information first encounters an individual through the sensory store; it is then processed in parallel in both a short-term and a long-term store.

Failures in memory for this model are suggested because of interference from new information that continually enters each of the stores (Atkinson & Shiffrin, 1971). They suggest that information that can be recalled is a result of rehearsal and reinforcement (1968; 1969; 1971). This simple model relies on pure rehearsal as the only manipulative factor, and yields little room for the effects of interference due to decay or similarity of current or new information with that of existing or newly acquired information.

Baddeley and Hitch (1974) further build upon the model by positing another component of the memory model termed *working* memory. They distinguish this from short-term memory in terms of its concurrent access. In other words, it is not just being stored temporarily, but is being recalled for action (for example in the dialing of a recently acquired phone number that was not written down). This working memory is further delineated in terms of specificity for verbal and nonverbal (spatial) information. Baddeley and Hitch demonstrated that the working memory could consist of more general process operations (such as recall or rehearsal) or modality specific manipulations (such as object rotation of visual stimuli). This working memory component is not to be ignored because it largely factors into the attention/concentration index of the TOMAL (discussed below).

Finally, the long-term store proposed by Atkinson and Shiffrin (1968; 1969; 1978) has been extensively investigated so that it is now apparent that there are a number dependent but interrelated forms of long-term memory that can be distinguished based on a number of features (e.g., type of information to be remembered, effortful vs. automatic encoding and retrieval). Figure 1 provides a summary of these various forms of long-term memory with the broadest distinction drawn between long term memory processes that are declarative or explicit in nature and those that are nondeclaritive or implicit in nature.

Declarative memories are those that are related to specific events in time. For instance, the name of your third grade teacher, or the cake that you had on your 16th birthday if recalled, would be specific events in time. The ability to use language and ride a bicycle are more common examples of implicit memory. Individuals typically access implicit memory without much thought or effort, yet at some time, there was unfamiliarity with the components involved in completing these tasks. Most likely, they arrived at their seemingly autonomous level of functioning through practice and rehearsal. It may in fact be that some of the components necessary for the creation of these nondeclaritive memory items began as more explicit facts, completely novel stimuli, or most likely a combination of both. It was through some form of rehearsal or practice that these novel tasks became implicit in nature. The importance of the distinction between these two broad categories is two-fold: first, it allows for a theoretical distinction between the types of memories that are typically studied, secondly, there is a good body of research that has demonstrated the preservation of one form of memory in the absence of the other (for a review of these see Thompson, 2000).

Summary and Implications of Memory Models

Regardless of the specific term used to describe the various constructs and models of memory, a general consensus about the nature of human memory does exist. It is one that consists of long-term storage of episodic, semantic, and procedural information as well as the short-term storage of useful information (such as upcoming meetings and appointments), and a component of manipulated informational processing within which we may manipulate both long-since consolidated information with that information which has much more recently been acquired and may or may not be consolidated. All of these domains may be impaired in TBI patients, and when we consider the implications for children who have not yet fully developed mature strategies for storage and retrieval, the identification of impairment in memory and other neurocognitive processes is critical.

It should also be noted that Figure 1 specifies neuroanatomical regions that are critical for the adequate function of the various types of long-term memory. Although the idea that specific neurocognitive functions are highly localized to a particular neuroanatomic region has been largely discarded in favor of a view of the cerebrum as a set of integrated circuits that work in cooperation to support higher cognitive functions, the key role of some brain structures in specific cognitive abilities cannot be denied and provide a basis for differential neurocognitive profiles arising from damage to different brain regions. For the present investigation, this point is critical as it is expected that the location of brain damage in children who sustain TBI is responsible for the neurocognitive heterogeneity observed in this population, and that attempts to parse this heterogeneity will provide insights into the brain regions that are most susceptible to injury as a result of TBI as well as clarity association among neurocognitive and behavioral deficits.

Studies such as the one proposed here have been largely hampered by the lack of available, reliable, and valid measures to assess neurocognitive and behavioral disturbances in children and adolescents. The next section describes some of the more popular measure and provides a rational for selection of measures for the current investigation.

Assessment of Neurocognitive and Neurobehavioral Function in Children

In recent years, many new tests have been developed to assess neurocognitive function in children. Two outstanding examples of such tests include the NEPSY (Korkman & Kirk, 1998) and the TOMAL. Both of these tests were developed specifically for children, i.e., they were not simply downgraded extensions of adult tests. They were both normed on large, representative samples of children. In addition, both might be better conceptualized as test batteries, as they are made up of a variety of tests which asses a number of different neurocognitive abilities. For the current investigation, the selection of tests was based upon several considerations. The TOMAL was selected for the current study because of its excellent psychometric properties, large stratified standardization sample, and its assessment of both short and long-term memory processes across both verbal and nonverbal information, as well as the assessment of attention/concentration abilities in addition to long-term memory. Also, it allows for the assessment of children across a broader age range (5.0 – 19.11 years) in comparison to the NEPSY (3.0 to 12.0 years) and has been shown to be sensitive to neurocognitive deficits associated with a variety of acquired and developmental neurological disorders (Howes, Bigler, & Lawson, 1999; Lajiness-O'Neill et al., 2005; Lowther & Mayfield, 2004; Morrison, 2006; Reynolds, 1998).

TOMAL Description

The TOMAL (Reynolds & Bigler, 1994) was specifically designed to assess attention, learning and memory in children in adolescents. It is a test made up of 10 core subtests and 4 optional tests. These subtests can be broken down into two distinct categories of verbal and nonverbal performance, and yield 4 core indices including Verbal Memory, Nonverbal Memory, Delayed Recall, and Composite Memory. Supplemental indices can also be calculated (Attention and Concentration Index, Sequential Memory Index, Free Recall Index, and an Associate Recall Index) and are used to provide additional information. The test was normed and empirically validated using a nationally stratified sample of children ranging in age from 5 to 19 years old based on the 1990 U.S. Census. The TOMAL has been shown to be sensitive to brain damage and yields valuable information regarding the impact of traumatic brain injury on core cognitive domains such as language, memory, attention, and learning (Lowther & Mayfield, 2004; Reynolds & Bigler, 1996).

Validity

The TOMAL has shown good validity with regard to both normal and clinical populations, and is sensitive to brain dysfunction in Attention Deficit/Hyperactivity Disorder (ADHD), as well as TBI, learning disability (LD), and certain genetic disorders (Howes, Bigler, & Lawson, 1999; Lajiness-O'Neill et al., 2005; Lowther & Mayfield, 2004; Morrison, 2006; Schmidt, 2003; Reynolds, 1998). It has also been shown to be highly correlated with performance on the WISC-III when examining children who have suffered from TBI (Schmidt, 2003). Reliability studies with the normative sample have also indicated that the TOMAL has excellent reliability (Bigler & Reynolds, 1996). Several studies have been conducted examining the factor structure of the TOMAL. One such study (Reynolds & Bigler, 1996) demonstrates the appropriateness of a four-factor solution that is consistent with the four main indices provided by the TOMAL. This study performed an exploratory factor analysis in order to obtain the best possible factor solution. A three and four factor solution was suggested, and the four-factor solution demonstrated the best fit. The resulting four-factor solution describes these factors as follows: a factor for general memory skills, a factor for sequential recall and attention, a factor consisting of backwards recall, and finally a spatial memory factor. When subsequently tested for the reliability of internal consistency, all indices had a high reliability coefficient that ranged between .94 and .99. (also see Alexander & Mayfield, 2005; Ramsay & Reynolds, 1995).

Reliability

The reliability of the TOMAL has been established using a representative national standard of children ages 5 to 19. Further, its reliability as an instrument that is sensitive to learning disabilities was established using a representative sample of children age 12 to18 who were enrolled in US public schools, and had a previously diagnosed learning disability (Reynolds, 1998; Reynolds & Bigler 1997).

Intellectual and Achievement Testing

A number of studies have evaluated children who have TBI with measures of intellectual functioning and achievement. With regard to IQ assessment, the WISC is by far the most used. Studies of children with TBI using the WISC have generally demonstrated that verbal abilities are less sensitive to the effects of TBI than tests of nonverbal/spatial abilities, referred to as performance tests. With the most recent versions of the WISC, four factors have been identified on which Index Scores can be computed including Verbal Comprehension, Perceptual Organization, Working Memory and Processing Speed. A number of recent studies indicate that the PS factor is sensitive to brain injury more so than the other index scores (Donders, Tulsky, & Zhu, 2001;

Hawkins, 1988; Ryan & Paolo, 2001; Taylor & Heaton, 2001). Despite the sensitivity of some of its factors to TBI, studies have generally determined that IQ tests are less sensitive to brain damage than neuropsychological measures (Reitan & Wolfson, 1986).

Children with TBI have also been evaluated with achievement tests including the Woodcock Johnson (WJ; McGrew, & Woodcock, 2001) and the Wide Range Achievement Test (WRAT; Wilkinson, 1993), the two most popular tests. Like IQ tests, achievement tests are less sensitive to brain damage than neurocognitive tests (Reitan & Wolfson, 1986). However, their measures of verbal abilities, like IQ tests, do provide valuable information regarding premorbid abilities and particularly intellectual functioning (e.g., Kremen et al., 1996)

Neurobehavioral Evaluation

In addition to neurocognitive and intellectual deficits following TBI, marked changes in behavior are often apparent. Problems with impulsivity and initiation are commonly reported, as well as difficulties with task persistence, irritability, and depression. For children, a number of methods have been developed to quantify these behavioral disturbances, with the most widely used system being the Behavioral Assessment System for Children (BASC).

Behavioral Assessment System for Children (BASC)

The BASC was designed to assist in making differential diagnoses of emotional and behavioral problems. By the use of three different rating forms, the BASC allows children, parents, and teachers to provide their evaluative perceptions of various aspects of the child's behavior that occur in social and academic settings. It can be used to assist in educational classification, treatment planning and for use in research. It is appropriate for children ages 2 to 18, and encompasses both internalizing and externalizing problem behaviors, as well as adaptive behaviors. It is comprised of 14 subscales that contribute five domains that can be used independently or in combination. One or all of the BASC rating forms can be used, including the Structured Developmental History, Parent Rating Scale, Teacher Rating Scale, Self Report of Personality and Student Observation System (Reynolds & Kamphaus, 1992).

Validity

A study using a sample of children referred for residential treatment was used to conduct a confirmatory factor analysis in order to examine construct validity of the BASC (Weiss & Smenner, 2007). This study revealed that while school maladjustment composite was limited, the personal and clinical maladjustment composites showed good convergent and discriminate validity. This suggests that the behavioral ratings provided should yield adequate measures, at a minimum, for the domains of clinical and personal maladjustment.

Reliability

Despite the recent development of excellent neurocognitive and behavioral measures for children and adolescents, few studies have used these measures to address the issue of neurocognitive heterogeneity in TBI. Those studies that have addressed this issue have typically used some form of cluster analysis of neurocognitive variables, given its widespread application in the social and biological sciences to identify subgroups or clusters in otherwise heterogeneous populations. The following section reviews the available cluster analytic studies from both the adult and child neuropsychological literature, to clarify areas that require further investigation and to provide a basis for the formulation of hypotheses for the current study

Cluster Analysis (CA) and TBI

Cluster analysis is a group of related multivariate taxometric procedures that allow for the reduction of data sets that are made up of heterogeneous objects into subsets of smaller homogenous groups. Objects in this sense can refer to individuals animals, people, rocks, weather patterns, economic indicators, etc., and so cluster analysis has proven useful in many fields of study including biology, epidemiology, marketing and psychology, to name a few. Psychological applications of cluster analysis have typically focused on people, and are concerned with identifying subgroups of individuals within heterogeneous groups, in order to better understand some aspect of behavior. For example, cluster analysis has been applied to disorders like schizophrenia in order to determine whether schizophrenia subtypes exist or conversely, whether it is better conceptualized as a single disorder that differs across a continuum of symptom severity.

In order to classify heterogeneous groups into homogeneous subsets (or clusters), cluster analysis examines the proximity (similarity or dissimilarity) of individuals within the larger group on a set of common variables in an attempt to group individuals who are similar each other in the same cluster. The common variables on which proximity is determined in cluster analysis are thought to be related to core features that would distinguish the various subgroups. Going back to the schizophrenia example, one might calculate proximity based on various symptoms (paranoid, disorganized, catatonic) to determine if clusters existed that represented paranoid, disorganized and catatonic subtypes. The focus on grouping individuals is the central difference between cluster analysis and factor analysis. While factor analysis typically focuses on grouping items together that measure a similar construct, cluster analysis focuses on grouping individuals who share similar traits or characteristics. (Some types of factor analyses are concerned with grouping individuals rather than items and are similar in this way to the cluster analytic procedures.) Thus, cluster analysis represents a statistical empirical approach to classification that can prove to be more informative for understanding the outcomes and prognosis of seemingly heterogeneous clinical groups such as TBI.

For disorders that are characterized by abnormalities in central nervous system function, neurocognitive variables have been used to elucidate the heterogeneity that is often present in various clinical groups. In fact, cluster analysis of neurocognitive variables has been used to provide insights into a variety of neurological, neurodevelopmental, and psychiatric disorders including Alzheimer's disease (Binetti et al., 1993; Fisher et al., 1996), HIV infection (Murji et al., 2003), schizophrenia (Allen et al., 2000; Heinrichs, Ruttan, Zakzanis, & Case, 1997; Seaton et al., 1999), learning disability (Snow, Cohen, & Holliman, 1985; Snow, Koller, & Roberts, 1987), and mixed neurological disorders (Goldstein & Shelly, 1987; Moses & Pritchard, 1996). Cluster analysis of neurocognitive variables has also been used to clarify the normal or expected variability in performance that occurs within non-brain damaged healthy individuals (Donders, 1996; Donders, Zhu, Tulsky, 2001).

Directly relevant to the current investigation, cluster analysis has been applied to investigate neurocognitive heterogeneity in traumatic brain injury (Crosson et al., 1990; Curtiss et al., 2001; Malec et al., 1993; Crawford et al., 1997; Wiegner & Donders, 1999;

Deshpande, Millis, et al., 1996; Millis & Ricker, 1994; Demery, Pedraza, & Hanlon, 2002). The majority of these studies have focused on adults with traumatic brain injury so relatively little is known about potential neurocognitive subgroups of children who have sustained TBI, although such subgroups are expected for a number of reasons. First, the literature with adults has demonstrated the presence of subgroups. Second, as previously discussed, because the mechanisms of cerebral injury in TBI are in fact heterogeneous (e.g., lacerations, contusions, DAI, stroke, seizure, hydrocephalus, edema, infection), a corresponding heterogeneous pattern of neurocognitive deficits is also expected which would be dependent on the type, severity and location of injury. Finally, depending on developmental stage, one might expect that TBI would affect brain function and development differently, i.e., similar injuries in a 5-year-old and a 15-year-old may produce markedly different patterns of neurocognitive dysfunction. It is also apparent that while many of these studies have identified subgroups or clusters of individuals with TBI, few have provided validity evidence for the clusters by including external validity variables that would shed light on, for example, the behavioral abnormalities that characterize and differentiate the neurocognitive clusters. In fact, this limitation probably extends past the cluster analysis literature on child TBI, as Gioia and Isquith (2004) have recently called for the use of a multimodal approach to assessment that incorporates functional behavioral analysis, and structured clinical interviews in addition to neuropsychological assessment, largely due to the heterogeneity of symptom presentation following TBI. Based on these considerations, the following sections review what is currently known regarding heterogeneity and neurocognitive function arising from TBI. This literature will serve as a basis for the hypotheses that are made in the current study.

Neurocognitive Functioning in Children Who have Sustained a TBI

The primary rationale for this study is the need to delineate homogenous subgroups from the larger heterogeneous group of child TBI patients. In doing so, we hoped to identify differences in patterns and/or levels of performance on a neurocognitive measure. It was hoped that this would better assist these children in terms of treatment and prognosis.

Several studies have demonstrated just how heterogeneous this group of individuals can be and have identified a number of factors that appear particularly important to understanding this neurocognitive heterogeneity, including demographic variables, premorbid condition, and developmental stage. While some controversy exists regarding the association of demographic variables on TBI outcomes, Donders and Nesbit-Greene (2004) found that higher SES is associated with better outcomes following TBI, although this contradicts findings of from other studies (Donders, 1996).

Premorbid function has also been examined as a contributing variable to neurocognitive heterogeneity following TBI. At least two areas have been examined in this regard, the first concerning overall level of intellectual ability prior to injury and the second concerning the presence of other conditions that are known to be associated with neurocognitive abnormalities and that occur at an increased incidence in those who go on to sustain TBI. With regard to premorbid intellectual ability, Yeats and Taylor (1997) found that of 80 children who sustained TBI, those with better premorbid ability had better prognosis following injury, potentially suggesting that those with greater cognitive or neural reserve are more resilient in the face of catastrophic brain injury. It is also the case that some disorders may occur at a higher rate in children who go on to sustain traumatic, including conduct disorder, attention deficit hyperactivity disorder (ADHD) and substance use disorders. As might be expected, the presence of these comorbid conditions can have a significant impact on neurocognitive abilities following TBI. For example, Slomine, Salorio and Grados (2005), report that TBI in children with ADHD (n = 82) exacerbates attentional and concentration problems.

With regard to developmental contributions to heterogeneity, Ewing-Cobbs, Fletcher, and Levin (1997) performed longitudinal evaluations of 79 children who had sustained traumatic brain injury at 6, 12, and 24 month following injury. Over this two-year period, variability in motor and cognitive functioning was apparent. Age of injury did not seem to affect differential performance. However, severe TBI for infants and toddlers had a global impact, suggesting an interaction between injury severity and age at the time of injury. Similarly, Lord-Maes and Obrzut (1996), in a review of the TBI literature, reported that when severity of injury was held constant, differential patterns of cognitive impairment are typically seen. These findings are consistent with other studies (Yeates & Taylor, 1997) that, based upon a comparison of 80 pediatric injury children (who served as comparison controls) and 109 TBI children have also found interactions between developmental level and the short- and long-term effects of TBI on neurocognition. In fact Kinsella, Prior, and Sawyer (1995), suggest that neuropsychological assessment is a useful tool in predicting educational outcome and special needs as early as 3 to 12 months post injury.

Verger, Junqué and Levin (2001) provide neuroimaging evidence for the contribution of neurodevelopment to neurocognitive heterogeneity following brain injury. Their study of 19 individuals who suffered a TBI as a child or adolescent were then compared to 19 matched controls in order to demonstrate that the neurocognitive function in adults can be predicted via MRI measurement of the 3rd ventricle and corpus collosum, while in children only the corpus collosum seemed to predict performance.

Thus, premorbid, neurodevelopmental and to a lesser extent demographic variables contribute to the variability in neurocognitive test performance following childhood TBI. As previously mentioned, a number of studies have used cluster analysis to investigate this heterogeneity and these studies are reviewed in the next section.

Cluster Analysis for Neuropsychological Data

In adults, cluster analysis has been used to differentiate the performance of adult TBI patients on adult intelligence tests (Heijden & Donders, 2003; Crawford, Garthwaite, Johnson, Mychalkiw, & Moore, 1997), neuropsychological test that assess domain specific and executive functioning tasks (Malec, Machulda, & Smigielski, 1993), and verbal learning and memory tests (Demery, Pedraza & Hanlon, 2002). Heidjen and Donders were able to identify clusters that were differentiated by level of education and injury severity. This differentiation was a general difference in the level of performance. Malec et al. were able to identify distinct clusters based upon a general pattern of performance. The factors seemingly influencing the pattern of performance were based upon the initial severity of injury, current level of neuropsychological impairment, and resulting disabilities. Consistent with this study's goal of treatment planning and prognosis, Demery et al. (2002) were able to identify clusters of verbal learning based upon the California Verbal Learning Test (Delis, Kramer, & Kaplan, 1994).

A number of studies of young to senior aged adults with TBI used cluster analysis in order to parse groups (Millis & Ricker, 1994; Deshpande, Millis, Reeder, Fuerst, & Ricker, 1996). In an evaluation of verbal memory abilities using the California Verbal Learning Test (CVLT; Delis, Kramer, Kaplan, & Ober, 1987) in 65 patients with TBI, Millis and Ricker (1994) found four different clusters based upon their differential retrieval and encoding abilities. Deshpande et al. (1996), in the same age group (n = 88), also used the CVLT to evaluate verbal memory for TBI patients and found 5 clusters, 3 of which are described as active, passive, or disorganized learning styles, while the other two clusters are described only as deficient.

In yet another study of memory abilities, Murji et al. (2003) combined both confirmatory factor analysis (in order to reduce the number of variables included in the cluster analysis to the most salient) and cluster analysis in order to identify clusters for individuals with HIV on the CVLT. Most importantly, this study demonstrated the usefulness of cluster analysis by examining the external validity of the derived clusters on external measures of overall neuropsychological performance and clinical evaluations. While these studies demonstrate the usefulness of cluster analysis, they are narrow in scope, due to their inclusion of only verbal memory based tasks.

Only two studies of children have applied cluster analysis to understand the heterogeneity in behavioral and neurocognitive dysfunction caused by TBI. Max, Sharma, and Qurashi (1997) used cluster analysis in an attempt to identify differences in the prevalence of Axis I and II diagnoses in children affected by TBI, compared to non-brain damaged controls. Neurocognitive abilities were not evaluated. Results indicated that there was no significant difference between TBI inpatients and matched controls, on the frequency of Axis I or Axis II diagnoses, unless the level of TBI was classified as severe.

Mottram and Donders (2006), attempted to identify clusters of differential performance on the children's version of the CVLT in a sample of 175 children with TBI. A cluster analysis was used to analyze the four variables that had the highest factor loadings (as determined by a prior factor analysis of a standardization sample for the CVLT-C). The cluster analysis consisted of a two-stage process that first used an agglomerative method (Ward's squared Euclidean distance) and was followed by a second stage that evaluated the appropriateness of fit and reassigned any poorly fitting individuals to the appropriate group (k-means method). Evaluation of the CVLT-C external validity for each of the clusters was achieved by looking at differences among groups based upon the severity of injury, demographic variables, and WISC-III index scores. The cluster analysis distinguished three of the clusters by level of performance (average, below average, and high average), while the fourth cluster was differentiated by pattern of performance (in that individuals demonstrated below average scores for all but one of the variables included, for which that variable was at an average level of performance).

While they were unable to differentiate a specific profile for the prognosis of performance on this test, Mottram and Donders were able to establish the relationship of injury severity, and the processing speed calculated using the WISC. This study also found that the clusters that were derived were not influenced by demographic variables included in the analysis. The lack of demographic influences in performance is important, because of previous findings that suggest parental level of education may be used to delineate clusters with differential performance on the WISC-III being seen in both the level and pattern of performance (Donders, 1996). Further this study was limited by a number of issues. First, the authors suggest that the location of sampling may contribute to the inclusion participants who had a greater level of injury than that seen in the population. Second, the authors state that data used for external validation was limited, due to the lack of consistent measure administration for each group (this is to say that there were very few members who had external data on the same instruments, e.g. the WISC-III). Therefore it would be beneficial to examine performance for a group with a broader range of injury severity, as well as one who has a greater amount of supporting data available for use in validation of the derived clusters. Further, the author suggests that future research examine other multimodal instruments that measure memory and learning in children with TBI.

The current study addresses the limitations of this prior study by including children with a broader range of injury severity, providing a more extensive evaluation of neurocognitive function, and examining a broader range of validity variables including behavioral ratings.

Summary

TBI has been shown to yield a very heterogeneous range of neuropsychological and behavioral symptoms. Many studies have been conducted in an attempt to classify TBI injury by performance scores on various measures, including scores on intelligence and neuropsychological tests, as well as by severity of injury (Alexander, 2003). However, few have attempted to identify meaningful, homogenous groups.

This study will use cluster analysis to identify homogenous groups based upon a combination of quantitative neurocognitive data from the TOMAL. A number of behavioral and clinical variables will be used, such as age, time since injury, severity of injury, premorbid IQ, and behavioral ratings, to establish the validity of the derived clusters.

Hypothesis

Based on the literature review, the following hypotheses are proposed:

1) A cluster analysis will reveal at least four different groups based upon patterns of performance on the TOMAL. One group will have average to above average performance on the TOMAL score, while another will exhibit generalized severe impairment. Two intermediate clusters will also be present, one characterized primarily by problems in attention/concentration, and the other with impairment learning and memory abilities. Thus both level and pattern of performance differences were hypothesized, although given the limited research in this area, prediction regarding additional clusters could not be made.

2) Clusters will differ on important clinical, demographic, IQ and behavioral variables which will provide support for their validity. Predictions regarding difference are made for two clusters differentiated on level of performance (normal and impaired). With regard to the IQ scores, the impaired cluster is expected to show lower overall scores than that of the normal cluster. When examining the clinical variables, the impaired cluster

will most likely have a higher GCS as well as a shorter time since onset of injury to assessment. Further, with regard to demographics, the age of injury is predicted to be younger for those in the impaired group than for those in the normal cluster (due to the critical stages of development that occur at younger ages, as discussed earlier). Finally, with regard to the behavioral variables, it is expected that we will see elevations in scores (indicating impairment or dysfunction) on all 14 of the scales, but they will likely be most evident in the composite scores of Externalizing Problems, School Problems and Adaptive Skills as well as the Behavioral Symptoms Index. Again, given the limited research in this area, more specific predictions regarding differences between the intermediate clusters could not be made.

CHAPTER 3

METHODOLOGY

Participants

The data used for this research was archival in nature. Participants consisted of children who suffered a traumatic brain injury. These children were seen as patients at Our Children's Hospital located at Baylor University in Texas, and were selected from a consecutive series of 523 cases seen over a 5-year period. Participants were initially selected for inclusion in the current study if they had a primary diagnosis of traumatic brain injury and had been administered the TOMAL. This initial selection resulted in 233 individuals being identified for inclusion in the analysis. The dataset was further reduced to exclude individuals who had multiple TOMAL assessments. As part of the initial data collection, individuals were assigned multiple case numbers for each assessment. For this study only the first assessment was selected for inclusion (for example, case1 could have been assigned the additional number of case 145 when assessed for a second assessment, and therefore only case 1 would be included). This reduced the data set from 233 to 216. Cases were also removed for which there was no TOMAL data present (n=19), and for which five or more of the 10 core subtests of the TOMAL were missing (n=10). This resulted in 187 participants being included in the cluster analysis. For all children, presence of structural brain damage was established comprehensive neurological evaluation utilizing appropriate neuroimaging, laboratory, and examinational findings. Definitive evidence of brain damage was present in all cases. Of these 187 participants, there were 110 males and 77 females. The average age of the sample was 12.3 years (SD = 3.7). They were assessed an average of 12.93 months (SD = 15.48, range = 5yrs 0 mo. to 18yrs 4 mo.) following injury. All children were seen as part of a broader neuropsychological assessment. As part of the assessment battery, standardized tests were used to assess severity of injury, intelligence neurocognitive and neurobehavioral functioning. All tests were administered by a pediatric neuropsychologist or doctoral level technician who was extensively trained in the valid and reliable administration of all testing procedures. Approval from the local IRB for protection of human subjects was obtained for this research.

Measures

Test of Memory and Learning (TOMAL)

The Test of Memory and Learning (Reynolds & Bigler, 1994) is a memory battery that is intended to measure a variety of domains in children 5 years 0 months to 19 years 11 months and 30 days. The authors (Reynolds & Bigler, 1994) state that the TOMAL is "intended to sample a variety of memory functions that are of clinical and theoretical interest for children and adolescents" (p. 1). This instrument is composed of 14 subtests, 10 core and 4 supplementary. Each subtest has a mean of 10 and a standard deviation of 3. The 10 core subtests are: Memory for Stories, Word Selective Reminding, Object Recall, Digits Forward, Paired Recall, Facial Memory, Visual Selective Reminding, Abstract Visual Memory, Visual Sequential Memory, and Memory for Location. The supplementary subtests are Letters Forward, Digits Backward, Letters

Backward, and Manual Imitation. The subtests combine to produce composite Core Indices: the Verbal Memory Index, Composite Memory Index, Nonverbal Memory Index, and Delayed Recall Index. Each index has a mean of 100 and a standard deviation of 15 (see Table 2 for a graphic representation). The Memory for Stories, Facial Memory, Word Selective Reminding and Visual Selective Reminding subtests all include a delayed task used to assess learning and decay of memory (see Table 2 for a graphic representation of the TOMAL index compositions; Reynolds & Bigler, 1994). Each summary score has a mean of 100 and a standard deviation of 15. Supplementary Indices can also be yielded from the subtests: Sequential Recall Index, Free Recall Index, Associative Recall Index, Learning Index, and the Attention/Concentration Index (see Table 2 for Indices and their composition).

Subtest Description

The Memory for Stories (MFS) is a verbal subtest that requires the participant to recall a short story that was read aloud by the examiner. This subtest provides a measure of sequential auditory processing and consolidation of verbal information with heavy demands on attention.

Facial Memory (FM) is a nonverbal subtest that requires recognition and identification of black-and-white photos from a set of distracters. The photos include examples of males and females of various ages and ethnicities. This subtest measures visual discrimination and retention of visual stimuli.

Word Selective Reminding (WSR) is a verbal free-recall task in which the participant is asked to learn a word list and repeat it. The words that are left out of the recall are reminded each time. Trials continue until all words are recalled or eight trials have been completed. This subtest assesses retrieval of verbal information from short- and long-term memory.

Visual Selective Reminding (VSR) is a nonverbal analogue to WSR in which the participant points out dots on a card after the examiner demonstrates. Eight trials are attempted unless mastery is achieved prior to eight trials. This subtest measures “pure” visual memory.

Object Recall (OR) is four trials are completed, in which the examiner names a series of pictures and the participant is asked to recall them. Verbal and nonverbal stimuli are paired in this task. The process of verbally recalling the paired stimuli is thought to create interference in recall for some children, and be neutral or helpful to others. This subtest assesses visual recognition paired with verbal recall.

Abstract Visual Memory (AVM) is a nonverbal task in which the participant is presented with stimuli and is asked to recognize that stimuli from an array of six distracter figures. This subtest is thought to measure the ability to process and retain abstract figures as complexity increases.

Digits Forward (DF) is a standard verbal number recall task that measures low-level recall of sequential information. This task is thought to measure verbal memory and attention.

Visual Sequential Memory (VSM) is a nonverbal task that measures recall of a sequence of meaningless geometric designs. The participant is exposed to the ordered designs, and is then asked to select the correct sequence from a standard array of the stimuli designs. This task is thought to be a higher cognitive process, and involves sequential visual processing and retention.

Paired Recall (PR) is a verbal paired-associate learning task. The participant is taught a sequence of paired words and is asked to recall the associated word when the examiner gives the other. Easy and hard pairs are given, along with a delay used to assess immediate versus associated recall and learning.

Memory for Location (MFL) is a nonverbal task that involves spatial memory. The participant is presented with a set of dots on a page, and is asked to recall the location of the dots in any order. This tasks taps into visual-spatial memory.

Letters Forward (LF) is a language related task that is analogous to a digit span task only with the use of letters. This subtest has both verbal memory and attention components.

Digits Backward (DB) is similar to the Digits Forward task, except the numbers are recalled in reverse order. This task is thought to measure working memory and attention.

Letters Backward (LB) is a language-related analog to the Digits Backward task using letters instead of numbers as stimuli. This is a working memory and attention measure (Reynolds & Bigler, 1994).

Index Score Description

Composite Memory Index (CMI) is a global indicator of verbal and nonverbal memory functioning. When deficits in both domains are present, it can be an indicator of diffuse memory dysfunction.

Verbal Memory Index (VMI) is a measure of verbal memory. Diminished performance in this domain may be indicative of left, usually dominant hemisphere dysfunction.

Nonverbal Memory Index (NMI) is designed to be a measure of nonverbal memory. This type of memory is thought to be mediated in the right or generally non-dominant hemisphere of the brain.

Delayed Recall Index (DRI) assesses delayed recall of both verbal and nonverbal information.

Sequential Recall Index (SRI) measures the ability to organize sequential input and output.

Free Recall Index (FRI) describes the ability to recall information without the aid of context clues.

Attention/Concentration Index (ACI) measures vigilance to the task as well as allocation of attentional resources.

Associative Recall Index (ARI) describes the participant's ability to learn paired stimuli.

Learning Index (LI) is a basic indicator of the retention and application of information.

Behavioral Assessment of System for Children (BASC)

The BASC is described by its authors (Reynolds & Kamphaus, 1992) as an instrument that relies on multiple methods of assessment of behavior and self-perceptions, assessed across a number of domains. It is made up of five reports of varying modality. The first report is a descriptive report of the child's observable behavior provided by the parent's and teacher of the child. These are known as the Parent Rating Scale (PRS) and the Teacher Rating Scale (TRS). The second component is the Self-Report of Personality (SRP), which allows the child to provide their own description of self-perceptions and emotions. A Structured Developmental History (SDH) is used to collect historical information, as well as a demographic description from the parents or other primary caregivers (such as a grandparent). The SDH is completed via an interview. The final component of the assessment system is the Student Observation System (SOS), which consists of a form for set up to classify various aspects of behavior that may occur in the classroom environment. These components were created with the intent of capturing both adaptive, as well as clinical (maladaptive) problems. Its goal is to assess both internal and external behaviors and feelings, as well as the feelings, cognitions and attitudes of the child.

The TRS has three different forms that are specific to a particular academic age range. These groups are: preschool (2 ½ - 5), child (6-11), and adolescent (12-18). Each form contains descriptions of behaviors for which the teacher is to rate frequency of occurrence on a 4-point scale. This scale ranges from *never* to *almost always*. The results of this form yield 14 scale scores as well as 5 composite scores (Externalizing Problems, Internalizing Problems, School Problems, Other Problems, and Adaptive Skills). Finally, it yields an overall composite score known as the Behavioral Symptoms Index (BSI).

The PRS is almost identical to the TRS. It however, does not include the School Problems composite score, and excludes the Learning Problems and Study Skills scales, because those items are best observed by the teacher.

The SRP consists of two age-range specific forms: child (8-11) and adolescent (12-18). Each form is designed as an inventory of personality containing true/false statements. Both forms yield three domain specific composite scores as well as a broad composite score consisting of: School Maladjustment, Clinical Maladjustment, and

Personal Maladjustment, with the overall composite of Emotional Symptoms Index (ESI).

The SDH may be completed either in an interview form by the clinician, or it may be administered in the form of a questionnaire. Regardless of the form of administration, it should be completed by the child's primary caregiver. The purpose of the SDH is to detect any family history, medical or developmental events that may have impacted the child's current behavior.

The SOS is a sampling based observational process, which records 3-seconds of behavior over a 30-second time-period. This process occurs for a duration of 15 minutes. Follow-up observations can be used to assess treatment effects.

The normative information for this instrument was collected from a large representative sample of the US population. This sample was evaluated for representativeness based upon age, gender, ethnicity, and parent education. They are reported by age range, and can be further divided by gender or combined (male and female) normative comparisons. Furthermore, the validity of the reports can be evaluated using three provided indices. These are: *F* (used to determine positive or negative response biases), *L* (used on the adolescent SRP to detect positive response bias), and *V* (used to identify endorsement of rare items).

Scales

Hyperactivity

The hyperactivity scale consists of items used to identify the two core symptoms of impulsivity and inattention in Attention Deficit/Hyperactivity Disorder.

Aggression

The majority of items for this scale consist of those used to detect verbal aggression. High scores (T-scores above 70), may warrant treatment intervention, because of the lack of tolerance for it.

Conduct Problems

This scale consists of items that meet are associated with juvenile delinquency and antisocial behavior.

Anxiety

This scale was developed with the intent of using items that are able to discriminate anxiety based symptoms from the often comorbid symptoms of depression and somatitization.

Somatization

This scale consists of a number of items that indicate physical complaints. Therefore, elevations (T-scores above 70) should be examined in conjunction with the SDH in order to discriminate medical based complaints from those of mental health issues.

Depression

This scale consists of items that report dysphoric and/or Dysthymic moods, attitudes, and behaviors. Due to the high comorbidity of depression with other disorders, the authors caution that the ESI is a more accurate indicator of Depression than the BSI.

Atypicality

These items consist of hallucinatory or psychotic features. However, the authors caution there may be some overlap with the hyperactivity or other scales that contain components of rumination (e.g., depression and somatitization).

Withdrawal

This scale was developed in order to differentiate shyness from pathological symptomology. It contains items that endorse problems with attachment and emotion.

Attitude to school and Attitude to Teachers

These scales do not correspond to a diagnosis of psychopathology, but may be used in the planning of treatment and the development of individual education plans for at-risk children.

Locus of Control

This scale was developed as a measure of external locus of control. Children who score high (T-scores at or above 70), typically demonstrate disruptive behavior, and therefore are typically involved in struggles for control with parents and teachers.

Sensation Seeking

The most clinically relevant information provided by high scores on this scale is the potential for sexual aggression in middle-school aged males. This scale is most accurately represented by the SRP and not the TRS.

Sense of Inadequacy

Adequacy for this scale is measured by academic performance. High scores for this scale tend to represent academic failures, and the authors suggest the need for treatment interventions after ruling out cognitive deficiencies.

Social Stress

This scale is interpreted based upon feelings of isolation and ostracism. These feelings are in relation to peers and not typically parents or teachers.

Adaptability

The adaptability scale measures the child's ability to adopt change. Unlike the preceding scales, high scores for this scale and those that follow portend positive aspects of behavior.

Leadership

This scale represents a combination of good social skills and cognitive capabilities, as well as good decision-making capacity. However, the authors report no clinically relevant findings for this scale.

Social Skills

While high scores portend well for a child on this scale, low scores may indicate a deficit that could be treated and can also assist in the differentiation of mental retardation and autism.

Study Skills

Low scores on this scale may assist in the development of a treatment plan by parents and teachers.

Self-Estee

This scale measures a negative self-view and perception that may best be captured by the SRP.

Self-Reliance

Similar to the Self-Inadequacy scale this scale consists of measures of academic performance, but also includes the endorsement of feelings of guilt or irresponsibility associated with those failures.

Wechsler Intelligence Scales for Children-Third Edition-Revised

The Wechsler Intelligence Scales for Children-Third Edition-Revised (WISC-III; Wechsler, 1991) is designed to measure cognitive ability and problem solving processes of children. The WISC-IV can be administered to children 5 to 16 years of age. The WISC groups an individual's ability into four global areas: Verbal Comprehension Index (VCI), which measures verbal ability; Perceptual Reasoning Index (PRI, which involves the manipulation of concrete materials or processing of visual information to solve problems nonverbally; Working Memory Index (WMI), which measures the auditory short-term memory; and Processing Speed Index (PSI), which measures cognitive processing speed/efficiency. These four Composite Indexes comprise the Full Scale IQ (FSIQ), which then serves as an estimate of general intellectual ability. Each Composite Index and Full Scale IQ yields a standard score with an average of 100 and a standard deviation of 15 (see table 1). The subtests that constitute each of the indexes have an average score of 10 and a standard deviation of 3 (see table 1). Percentile ranks are also reported for each score. A percentile rank describes a child's standing relative to same-age peers. The percentile rank indicates the percentage of same-aged peers who performed at the same level or below. For example if a child performs at the 20^{th} percentile, he/she performed similarly to or better than 20 out of 100 (or conversely lower than 80 out or 100) same-aged children.

The VCI is a measure of crystallized intelligence. The VCI is made up of tasks that require the ability to define words (Vocabulary), draw conceptual similarities between words (Similarities), and answer questions involving knowledge of common sense and social situations (Comprehension).

The PRI is a measure of visual processing and fluid reasoning using tasks that require the recreation of a series of modeled or pictured designs using blocks (Block Design), identification of the missing portion of an incomplete visual matrix from one of five choices (Matrix Reasoning), and the selection one picture from each of two or three rows of pictures to form a group with a common characteristic (Picture Concepts).

The WMI is a measure of short-term memory as measured by the ability to apprehend and hold or perform an operation on information in immediate awareness and then use it within a few seconds. This ability is assessed by two tasks. Digit span requires one to repeat sequences of numbers in the same order as presented by the examiner (Digit Span Forward) and in the reverse order (Digit Span Backward). Letter-Number-Sequencing requires one to listen to a sequence of numbers and letters, and recall the numbers in ascending order followed by the letters in alphabetical order.

The PSI is a measure of processing speed, and represents the ability to fluently and automatically perform cognitive tasks, especially when under time pressure to maintain focused attention and concentration. This ability is assessed by two tasks. The first requires one to quickly copy symbols that are paired with numbers according to a key (Coding). The second task requires one to identify the presence or absence of a target symbol in a row of symbols (Symbol Search).

For the current study, the composite scores will be used because they have been well-established using factor analysis and provide a more reliable estimate of cognitive ability compared to individual subtest scores (Donders, , & Warschausky, 1996; Donders, 1997a; Donders, 1997b; Konold, Kush, & Canivez, 1997; Tupa, Wright, & Fristad, 1997; Roid, & Worrall, 1997; Grice, Krohn, & Logerquist, 1999; Watkins, Greenawalt, & Marcell, 2002; Watkins, & Kush, 2002; Mccrowell, 2005).

Glasgow Coma Scale (GCS)

The Glasgow Coma Scale (Teasdale & Jennet, 1974) is used for assessing the severity of head trauma while the person is still in the acute posttraumatic state. Scores on the GCS range between 3 and 15, with 3 suggesting severe impairment, and 15 being considered functional. The severity of neurobehavioral deficits are categorized by GCS scores into mild (13-15), moderate (9-12), and severe (3-8), with scores of 8 or less being generally indicative of a comatose state (Teasdale & Jennett, 1974; Jennett & Teasdale, 1981; Lezak, Howieson, & Loring, 2004). It is composed of three areas: Best Eye Response (Score 1-4), Best Verbal Response (Score 1-5), Best Motor Response (Score 1-6) (see Table 2). The GCS's scaling system provides objectivity, reproducibility, and simplicity. The GCS has a high degree of inter-rater reliability.

Data Analysis

Cluster analysis is a multivariate approach that attempts to group data based on natural interrelations so that groups will show high levels of homogeneity within each cluster and high levels of heterogeneity between clusters (Hair et al., 2005). Hair et al. suggest that the strength of cluster analyses is that it allows for classification based on inherent characteristics of individuals within the sample (for an complete overview of cluster analysis, see Everitt, Landau, & Leesee, 2001). In the current study, cluster analytic methods were used to classify patients with TBI based on their TOMAL subtest scaled scores.

Several steps are required in cluster analyses: (a) identify the participants of the study; (b) select the variables to be used; (c) choose the clustering procedure and way to measure similarity, and (d) choose the number of clusters to include in the final solution (Hair et al., 2005; Morris, Blashfield, & Satz, 1981, Lange et al. 2002). The participants and variables have been described in some detail above. Following is a description of the clustering procedures.

Variable Selection for the Cluster Analyses.

The focus of variable selection in cluster analytic research is to choose variables likely to be "characteristic of the objects being clustered" and pertinent to the goals of the analysis (Hair et al., 2005). Unstudied variable choices can unwittingly lead to clusters that are less than meaningful due to differences that are not related to the objectives of the research. For example, hair color would not likely be a helpful variable when investigating traumatic brain injury. Some might question whether a memory test such as the TOMAL is sensitive enough to effectively measure areas of functioning that might differ between independent subgroups within the more general TBI population. To address this, it is first important to consider that the variability in acquisition, the nature of the initial symptomology, and the resulting secondary damage, as previously discussed (Bigler & Clement, 1997; Bigler, Kurth, Blatter, & Abildskov, 1993; Smith et. al. 1998; Hannay et. al., 2004), makes it necessary for us to use a comprehensive measure such as the TOMAL. It is also relevant to note that since the TOMAL has been demonstrated to be sensitive to brain injury, performance on the TOMAL is a direct index of the biological status of the brain, or put another way, the integrity of the various neural circuits that give rise to complex cognitive activity. With regard to variability in neurocognitive deficit arising from injury to different areas of the brain, the TOMAL emphasizes learning and memory abilities (including verbal and non-verbal) as well as working memory or attention. Given that the frontal and temporal lobes are particularly susceptible to injury in TBI (especially in MVA involving acceleration or deceleration injuries) and that intact function of these areas has been shown to be critical for normal memory and attention function, the TOMAL's emphasis on these abilities should allow for the observation of significant variation among subjects that depends on specific lesion location, and to a lesser extent, mechanism of injury. It is also relevant to note here, that the TOMAL's division of assessment procedures into verbal and nonverbal/spatial modalities should provide additional sensitivity to lesions lateralization, allowing for variation in test performance to be observed based on the extent of involvement of one hemisphere or another.

Finally, aside from these neuroanatomical and brain-behavior considerations, neurocognitive tests such as the TOMAL have been demonstrated to significantly predict treatment outcomes, both short and long term. Based on these considerations the TOMAL variables that were entered into the cluster analysis consisted of the standard scores for each of the subtests described above.

Clustering Method

The clustering method, or algorithm, chosen to empirically group cases can be quite important since different approaches can derive different cluster solutions based on the same data (Hair et al., 2005). Cluster analyses can also derive "clusters" from randomly generated data sets (Morris et al., 1981). Therefore, the choice of clustering method is important since it may have direct impact on the findings of the analysis.

A hierarchical agglomerative clustering method, Ward's method, was utilized in the current study. This method of cluster analysis begins by pairing the most similar (as measured by squared Euclidean distance) subjects into a group. This process is continued by grouping the most similar clusters until all of the observations are included (Hair et al., 2005). Ward's method was utilized because it allowed for consistency with the cluster analytic methodology of previous studies conducted in this area of research (Mottram & Donders, 2006; Curtiss, et al., 2001). Furthermore, Ward's method produces results that are consistent with other agglomerative clustering method and has the advantage of being less affected by outliers, which was an important consideration for TBI data, which often has substantial variability. In this method, possible associations among subjects are analyzed and subjects are clustered in a manner that attempts to keep the error sum of squares as low as possible (Morris et al., 1981).

Measure of Similarity

Typically, similarity between participants is measured utilizing distance measures (Hair et al., 2005). By measuring how different two participants are on the measures of interest, one is able to gain information about their level of similarity. The Squared Euclidian distance measure was utilized in the current investigation as the measure of similarity. Squared Euclidean distance is an algebraic "measure of the length of a straight line between two objects" (p.266, Hair et al., 2005) and is among the most widely used distance measures. It was chosen in this case to be consistent with the previous research in this area, and because it has been shown to be sensitive to pattern of performance and level of performance differences among individuals.

Choosing the Number of Clusters

Based on the hypothesis, we examined three, four and five cluster solutions in order to determine the most appropriate number of clusters. This was determined first with an inspection of the graphical output of the cluster analysis software. The hierarchical trees were inspected to ensure that outliers or a phenomenon known as chaining has not occurred. Chaining and outliers are related since chaining occurs when the cluster analysis program derives clusters constituted primarily by outliers (Morris et al., 1981). Inspection of the hierarchical trees and cluster coefficient outputs can also reveal whether there is an increase when agglomerating between clusters. Such increases can represent a point where dissimilar clusters are being joined, or agglomerated (Hair et al., 2005). By graphing the clusters in discriminant function space, a graphical method of inspection of the overlap between each cluster can also help to assess the adequacy of the cluster solution (as suggested by Aldenderfer & Blashfield, 1984). It is anticipated that for an adequate cluster solution, the clusters will be fairly well separated when plotted in discriminant function space.

The stability of the cluster solution was also evaluated using the K-means iterative classification process. The K-means iterative partitioning method of cluster analysis derives cluster solutions from data sets by beginning at the opposite end of that used in agglomerative methods. In this method, the number of clusters and initial centers are specified for each individual cluster (Hair et al., 2005). In the current study, the centers for each cluster were based on the mean scaled scores for each of the respective TOMAL subtest scaled scores. These mean scores were calculated based upon the clusters derived through Ward's method. The K-means iterative partitioning method derives cluster membership by assigning subjects to clusters by analyzing and finding those cases most similar to the experimenter-designated centers (Morris et al., 1981). Following the placement of all subjects into clusters, the program analyzes the data for variables that do not belong in clusters and either respecifies them to other groups or drops them from the analyses all together (Morris et al., 1981). While the K-means clustering method can be utilized in and of itself for empirically classifying observations, in the current investigation it was utilized to assess stability of the cluster solution derived by Ward's method. Had the K-Means approach calculated a significantly different cluster solution, questions would exist as to whether the initial Ward's method-derived solution was stable. The centers for each of the TOMAL subtests, derived through the Ward's method, were specified as the starting points for the K-means clustering method and the cluster solution. The extent to which the K-means and Ward's method solutions agreed was measured by using Cohen's Kappa. Finally, an F-statistic proposed by Beale (1969) was used to determine if the final cluster solution was parsimonious by comparing the final cluster solution to less complex solutions. Based on these various methods, the most appropriate cluster solution was identified.

External Validation of the Cluster Solution.

Following identification of the number of clusters, the validity of the solution was be examined using a number of variables that were not included in the cluster analysis but that are theoretically and clinically relevant to traumatic brain injury. Since there are many different approaches to cluster analysis that might produce quite different results, an important aspect of such analyses is this type of external validation of the clusters (Morris et al., 1981). In this study, external validity was evaluated by conducting various ANOVAs for the available IQ (WISC-III, WISC-IV, and WPSI), achievement (WJ-III) and behavioral data (BASC).

CHAPTER 4

RESULTS

Data Screening

In order to determine the appropriateness of the scores for cluster analysis, kurtosis and skewness values, stem-and-leaf diagrams, and normality plots were inspected. Appropriateness was assessed for the scores on the TOMAL to ensure that the sample was normally distributed. Box plots were used to identify outliers. For the purposes of this investigation, outliers were defined as scores 2.5 standard deviations above or below the sample mean. When identified, outliers were transformed using standard procedures (Tabachnick & Fidell, 2001). Additionally, when correcting for the influence of outliers did not narmalize the distribution of the data, the data were transformed. With the TOMAL subtest scaled scores there was no need to calculate new standardized values since they are standardized scores derived from the participants' raw scores on the individual subtests of the TOMAL.

Preliminary Analyses

Demographic and clinical data are presented in Table 1. Upon examination of the demographic information for these data, a few interesting variables stand out. This sample is predominantly composed of Caucasian, male patients. They were on average 12.3 years of age and were assessed approximately 1 year after they had sustained injury.

Of the 187 patients with TBI, the largest portion (53.5%) of cases was caused by a motor vehicle accident (MVA). Of those involved in a motor vehicle accident, half were restrained, while 27% were not restrained. The second greatest cause for TBI was a pedestrian versus a motor vehicle (20.9%). Nearly all (92%) of the brain injuries were classified as a closed head wound. Only 8 of the 187 patients had a secondary diagnosis beyond the primary diagnosis of TBI. Glasgow Coma Scale scores were available for 127 participants and indicated that on average, they had sustained severe brain injury.

The overall performance on the individual TOMAL subtests, as well as the index scores, can be seen in table 2. This summary of the results demonstrates that, as a group, performance on the TOMAL Index scores was approximately 1.33 standard deviations below the standardization sample mean, or in the mildly impaired or low average range (Reynolds & Bigler, 1994). As might be expected, significantly more variability is observed for the individual subtest scores, which were subsequently used in the cluster analysis.

Analysis of Main Hypotheses

Cluster solutions were derived using Ward's method for three, four, and five cluster solutions. Table 3 represents the results of a three-cluster solution for the sample's TOMAL data. Table 4 represents the results of a four-cluster solution for the sample's TOMAL data. Table 5 represents the results of a five-cluster solution for the sample's TOMAL data.

A preliminary examination of the cluster solutions based on the TOMAL subtest scores was not particularly informative because the number of subtests made graphical interpretation difficult. For example, Figure 2 presents the TOMAL subtest scores for each of the clusters in the 5-cluster solution. As can be seen from the figure, variability in subtest scores is present across the clusters but interpretation of differences is difficult due to the sheer number of variables. Because of this variability and difficulty interpretation, an alternative approach was selected to examine differences in TOMAL performance among the various cluster solutions in which the main index scores were plotted. Figure 3 contains the results of this method for the 3-, 4-, and 5- cluster solutions.

As can be seen from Figure 3, the three-cluster solution differentiates the groups by level of performance. One cluster is best characterized as an Average cluster, obtaining average scores on the TOMAL indexes with its lowest score on the Attention Concentration Index. The second cluster could be best described as a Low-Average cluster, exhibiting low average performance on the TOMAL indexes. The final cluster is an impaired cluster, scoring two or more standard deviations below the standardization sample mean on all of the TOMAL index scores. Some variability in pattern of performance is also apparent, particularly for the Impaired cluster (C2 for the 5-cluster solution, figure 3), although differences in pattern of performance among the three clusters tends to be minimal.

For the four-cluster solution, the clusters are differentiated by both level and pattern of performance. In comparison to the three-cluster solution, the four-cluster solution maintains the Impaired and Average clusters, but also identifies two intermediate clusters that are primarily differentiated by performance on tests of verbal and nonverbal memory. One of these clusters exhibits better performance on the nonverbal memory index than the verbal memory index and is referred to as the Verbal Memory cluster (C5 for the 5-cluster solution, figure 3). The other cluster exhibits better performance on the verbal memory index than the nonverbal memory index and is thus referred to as the Nonverbal Memory cluster (C1 for the 5-cluster solution, figure 3).

Clusters in the five-cluster solution are also differentiated by level and pattern of performance differences. The five-cluster solution maintains the Impaired, Verbal Memory, and Nonverbal Memory clusters identified in the four-cluster solution. However, the Average cluster is divided into two clusters, one with average performance on all of the TOMAL index scores (Average cluster; C4) and a second that exhibits a relative deficit on the TOMAL Attention/Concentration index, referred to as the Attention cluster (C3). It is interesting to note that unlike the average cluster identified in the three and four cluster solutions, the Average cluster identified in the five-cluster solution exhibits uniform performance close to the standardization sample mean on all of the TOMAL indexes with no relative deficit on the Attention/Concentration Index. Those individuals who demonstrated relative deficits on the Attention Concentration Index in the lower-level solutions were separated out into their own cluster (Attention cluster) in the five-cluster solution primarily based on poor performance on the Attention/Concentration Index. Thus, preliminary inspection of the three-, four- and five-cluster solutions suggests that the four and five cluster solutions provide a clear indication of level and pattern of performance differences, with this being the case particularly for the five-cluster solution, which also appears to be the most theoretically and clinically interesting of the solutions.

In order to further explore the stability of the five-cluster, hierarchical trees for each solution were inspected to ensure that outliers or chaining had not occurred. Inspection of the dendogram revealed no evidence of chaining, suggesting that the cluster solution was not negatively impacted by outliers. An inspection of the hierarchical trees and cluster coefficient outputs revealed an increase when agglomerating between clusters, representing points where dissimilar clusters are being joined, or agglomerated (Hair et al., 2005). Graphing the clusters in discriminant function space indicated that the clusters were fairly well separated (see figures 4, 5 and 6), though, as often is the case, there was some overlap. The discriminant function analysis reclassification process also demonstrated a stable cluster solution for all of the cluster solutions derived (See tables 6,7 and 8 for reclassification rates).

The stability of the three-, four- and five-cluster solutions were next evaluated using the K-means iterative classification process. The centers for each of the TOMAL subtests, derived through the Ward's method, were specified as the starting points for the K-means clustering method and the appropriate number of clusters derived using Ward's method were also specified. The extent to which the K-means and Ward's method solutions agreed was measured by using Cohen's Kappa. Results of these agreement analyses indicated that the Cohen's Kappas for the three-, four- and five-cluster solutions were .79, 75, and .79, respectively. For all of the cluster solutions these Kappas are at or above a level considered excellent. This level of agreement demonstrates that the cluster solutions derived from Ward's method was stable and had a high level agreement when using a non-agglomerative clustering procedure (see Tables 9-11 for a comparison of clustering classification between Ward's method and K-means iterations and their level of agreement based upon the results of Cohen's Kappa). The five-cluster solution had a higher Kappa than the 4-cluster solution but was equal to that of the 3-cluster solution.

Finally, the cluster solutions were evaluated using a test first proposed by Beale (1969). Beale's F-statistic evaluates the clusters for homogeneity by comparing the sum of the squared Euclidian distances to the cluster centroids. This F-value is than evaluated against the critical values of the F-distribution. If the critical value is exceeded then the cluster solution is thought to be a statistically better division, than the one to which it was compared. Thus, this statistic allows for a determination of significant differences between cluster solutions based the F-distribution. Analyses indicated that the 4-cluster solution accounted for significantly more variance than the 3-cluster solution, $F\,(13, 2045) = 2.83, p < .001$, and that the 5-cluster solution was also significantly better than the 3-cluster solution, $F\,(26, 2392) = 2.22, p < .001$. The difference between the 4- and 5-cluster solutions was not statistically significant, $F\,(13, 2392) = 1.37, p = 0.17$, although the difference was in the expected direction with the 5-cluster solutions accounting for more variance than the 5-cluster solution.

External Validation of the Five Cluster Solution

In order to establish the validity of the five-cluster solution, a number of external validation variables were examined including differences in demographic and clinical variables among the clusters, as well as potential differences in intellectual, achievement and behavioral test performance. With regard to clinical and demographic differences, it was predicted that age of injury would be younger for those in the impaired group than for those in the normal group. Descriptive statistics for the demographic and clinical variables according to cluster are presented in Table 12.

Chi-square analyses further indicated that there were no significant differences among the clusters with regard to gender, χ^2 (4) = .21, p = .99, ethnicity, χ^2 (16) = 18.97, p = .27, or TBI type, χ^2 (4) = 5.90, p = .20. Univariate ANOVAs indicated that the groups significantly differed with regard to current age, F (4, 182) = 4.55, $p < .01$, age at the time of injury F (4, 180) = 4.84, $p < .01$, and Glasgow Coma Scale scores, F (4,116) = 2.57, $p < .05$. However, there was not a significant effect for the time between injury and assessment, F (4, 180) = .143, p = .97. Post hoc analyses (Tukey) indicated that for both current age and age at the time of injury, the Average cluster (C4) was significantly older ($p < .05$) than the Impaired (C2), Attention (C3) and the Verbal (C5) clusters, but did not differ from the Nonverbal Cluster (C1). For Glasgow Coma Scale scores, post hoc analyses revealed that the Impaired Cluster (C2) had significantly lower scores than the Attention Cluster (C3), and no other differences were present among the clusters. However, the expected pattern of performance was present, with the Impaired Cluster receiving the lowest overall score. Differences among the groups on Age and Glasgow Coma Scale scores are presented in Figures 7 and 8.

External validity was further evaluated by comparing the clusters on IQ variables. It was hypothesized that the Average group would have significantly higher IQ scores than the impaired group, although more specific predictions were not made with regard to IQ differences because of a lack of existing literature upon which to make such predictions. Comparisons on the general IQ indexes indicated that the Average cluster (C4) did indeed attain significantly higher IQ scores than the Impaired cluster (C2) on Verbal IQ, t (63) = 9.07, $p < .001$, Performance IQ, t (63) = 8.26, $p < .001$, and Full Scale IQ, t (69) = 10.05, $p < .001$. Respective means for the Average and Impaired groups were 101.03 (*sd* = 15.17) and 74.17 (*sd* = 8.14) for Verbal IQ, 94.23 (*sd* = 12.07) and 68.23 (*sd* = 13.13) for Performance IQ, and 96.81 (*sd* = 14.39) and 68.93 (*sd* = 8.86) for Full Scale IQ.

More detailed analyses were undertaken in order to examine potential differences between the clusters on the Wechsler Index scores. However, prior to conducting these analyses, two steps were taken in order to maximize the amount of IQ data available for analysis. First, since children were tested over a period of more than 5 years and were of markedly different ages, a number of versions of the Wechsler Intelligence scales were administered including the WISC-III, WISC-IV, and WPPSI. Given that these versions of the Wechsler scales share many common subtests and that these common subtests are designed to measure the same abilities across age groups and test versions, data were combined across the various Wechsler tests. Second, rather than analyzing the four Index Scores, individual subtests were analyzed which have been shown in previous research to be the best measures of these index scores (e.g., Reynolds & Ford, 1994). Thus, the Verbal Comprehension Index was measured using the Vocabulary subtest, the Perceptual Organization Index was measured using the Block Design subtest, the Working Memory factor was measured using the Digit Span subtest, and the Processing Speed Index was measured using the Digit Symbol/Coding subtest. Prior to comparing the clusters on these subtest scores, the factor structure of the available Wechsler data was examined using principal components analysis with varimax rotation, and with four factors specified. The rotated factor matrix is presented in Table 13 and is largely consistent with prior studies, providing some assurance that the steps used to maximize the number of cases for the IQ analysis did not appreciably affect the factorial validity of the individual subtests.

A repeated measures ANOVA was then conducted in which Cluster membership (1 – 5) served as a between subjects variable and Wechsler subtests were the repeated measure (Vocabulary, Block Design, Digit Symbol/Coding and Digit Span subtests). For these analyses there was significant effects for Cluster, $F(4, 137) = 32.50, p < .001$, significant effects for IQ, $F(3, 411) = 8.67, p < .001$, as well as a significant the Cluster by IQ interaction, $F(12, 411) = 2.61, p = .002$. The interaction effect is presented in Figure 9 and descriptive statistics are presented in Table 14. As can be seen from the figure, the interaction effect appears to be caused primarily by decrements in performance on the Coding (CD) subtest for the Average cluster (C4) and Attention Cluster (C3), as well as a slightly diminished performance on the Vocabulary subtest (VO) by the Verbal Cluster (C5) and a somewhat improved performance on the CD subtest by the Impaired cluster (C2). Finally, consistent with the hypothesis regarding more general IQ differences between the Average and Impaired clusters, visual inspection of the subtest scores presented in Figure 9 provide clear evidence for the superiority of the Average cluster (C4) over the Impaired cluster (C2).

No hypotheses were made regarding the achievement test data and so these analyses were viewed as largely exploratory in nature. For the achievement data, a repeated measures ANOVA was conducted in which Cluster membership served as the between subjects variables and the WJ3 Composite Scores served as the repeated measure. The composite scores of Broad Reading, Broad Math, and Writing Samples were chosen, again in order to achieve maximal inclusion of data (see table 15). The analyses revealed a significant effect for Cluster, $F(4, 47) = 4.97, p = .002$. However there was no significant effect of WJ3 Composite Score, $F(1, 47) = 2.46, p = .12$, nor was there a significant effect for the interaction of Cluster by WJ3 Composite Score, $F(4, 47) = .94, p = .45$. The significant effect for cluster indicated that for the Broad Reading and Broad Math Composites, the Impaired Cluster (C2) obtained significantly lower scores than the Average (C4) and Attention (C3) clusters, with no other differences present among the clusters. For the Writing Skills Composite the only difference that was present was between the Impaired cluster (C2) and the Attention cluster (C3), with the Attention cluster obtaining significantly higher scores.

For the behavioral data, separate repeated measure ANOVAs were conducted for the composite scores of each of the BASC report forms, one for the Parent, one for the Teacher form, and one for the Self-report form. For the Parent Report form, a repeated measures ANOVA was conducted with cluster membership serving as a between subjects variables and the BASC composite scores consisting of Internalizing Problems, Externalizing Problems and Adaptive Skills as the within subject's variable. Because the variables of Internalizing and Externalizing problems are keyed opposite of Adaptive skills (i.e., higher scores equal impairment for problems, while higher scores for skills indicate compensation), the score for Adaptive skills was achieved by subtracting it from 100 (the top of the scaled score). For this analysis there was no significant effect for the BASC Composite Score $F(2,334) = 2.19, p = .11$, Cluster membership, $F(4, 167) = 1.48, p = .21$, nor was there a significant effect for the interaction of Cluster by Composite Score $F(8, 334) = .25, p = .91$ (See Figure 10).

For the Teacher Report form, a 5 X 4 (Cluster X Composite Score) repeated measures ANOVA was conducted with the levels of cluster being 1 through 5 and the composite score consisting of internalizing problems, externalizing problems, school problems and adaptive skills as the within subject's variable (see figure 11). The results of the analysis indicated that there were no significant effects of Cluster, $F(4, 55) = .951$, $p = .44$. However, results did indicate there was an overall effect of BASC score, $F(2, 166) = 20.12, p < .001$ as well as a significant interaction effect of Cluster X BASC Score (Teacher Report Form), $F(12, 165) = 4.221, p < .001$.

In order to examine cluster differences for the BASC Self Report form, a 5 X 3 (Cluster X Composite Score) repeated measures ANOVA was conducted with the levels of cluster as the between subjects variable (Clusters 1 through 5) and BASC scores as the repeated measure (School Maladjustment, Clinical Maladjustment and Personal Adjustment). Results of the analysis indicated that there were no significant effects for Cluster, $F(4, 134) = 1.36, p = .25$, or BASC score, $F(2, 268) = .85, p = .43$, although the Cluster by BASC interaction effect approached significance, $F(8, 268) = 1.78, p = .08$. As seen in Figure 12, cluster 1 has a Clinical Maladjustment Score that is above average, with an average School Maladjustment Score and a slightly below average Personal Adjustment Score. Figure 12 also shows that while cluster 4 has slightly below average clinical and school maladjustment scores, this clusters Personal Adjustment Score is slightly above average.

CHAPTER 5

DISCUSSION

Due to the heterogeneous nature of TBI, this study was designed to determine if homogeneous subgroups might be identified in a sample of children and adolescents who had sustained a TBI. It was hypothesized that the identification of homogenous clusters of TBI patients would provide important information regarding typical differences in level and pattern of performance on a standardized neurocognitive test (TOMAL) of memory and attention. It was further hypothesized that the external validity of these homogenous subgroups would be demonstrated by differences on measures of intelligence, academic achievement, and behavior as well as important clinical and demographic variables. The results of the study provide some support for the proposed hypothesis.

With regard to the presence of homogeneous subgroups within the larger sample of children with TBI, examination of the TOMAL subtests did suggest that sub-groups that are more homogeneous were present. While three and four cluster solutions were derived, ultimately the five-cluster solution was chosen for evaluation against the aforementioned external measures of validity. Both theoretical and clinical considerations lead to the selection of the 5-cluster solution over the more parsimonious 4- and 3-cluster solutions. Both the 4 an 5 cluster solutions accounted for significantly more variance than the 3 cluster solutions providing a theoretical basis for their acceptance over the simpler 3 cluster solution. It is also relevant to note that based on the available literature, a 4-cluster solution was proposed *a priori* as the optimal solution that also supports the acceptance of a higher-order solution.

In selecting between the 4 and 5 cluster solutions, the hypothesis regarding the number of clusters was also instructive. Specifically, it was hypothesized that one cluster would have average to above average performance on the TOMAL, while another would exhibit generalized severe impairment. Two intermediate clusters were also hypothesized, with one characterized primarily by problems in attention/concentration and the other with impairment learning and memory abilities. The 4-cluster solution (see Figure 3) was consistent with the hypothesis in that average and impaired clusters were identified, as were two intermediate clusters. Contrary to predictions however, the two intermediate clusters were characterized by what is best described as selective deficits in either verbal or nonverbal memory abilities. Thus, the hypothesized attention deficit cluster was not present in the four-cluster solution. Interestingly though, when the five cluster solution was examined, the anticipated attention deficit cluster emerged, although not as a cluster intermediate to the average and impaired groups, but rather as an otherwise average group that displayed a relative deficit in the area of attention and concentration. Based on these considerations, the five-cluster solution was selected as the optimal solution.

The current number of clusters is largely consistent with prior studies, which found cluster solutions ranging from three clusters (Heijden & Donders, 2003; Crawford, Garthwaite, Johnson, Mychalkiw, & Moore, 1997), typically distinguished by pattern of performance, to solutions of four and five clusters which extended previous findings to include groups which are also differentiated by pattern of performance (Malec, Machulda, & Smigielski, 1993; Millis & Ricker, 1994; Deshpande et al. 1996). While the possible reasons for this difference could not be directly evaluated in the current study, a number of methodological differences may account for these apparently discrepant findings. Probably most importantly, some prior studies have relied on measures of a unitary cognitive domain (e.g., verbal memory as measured by the CVLT; see Mottram & Donders, 2006; Donders, 1996) which limited their ability to observe modality specific differences (visual vs. verbal) or differences in patterns of impairment across different cognitive domains (attention vs. memory impairment). This study was also limited by the restriction of range with regard to severity of injury. With regard to the former point, cluster differences defined primarily by deficits in verbal and nonverbal memory domains were identified in the current study, as were clusters defined by differential performance across such diverse cognitive domains as memory and attention. With regard to the latter point, this study addressed the restriction of range by using a larger sample with a broader range of TBI severity. It may be that employing the TOMAL allowed for the identification of a more complex pattern of neurocgnitive deficits than what had been identified in prior studies.

The second hypothesis dealt primarily with demonstrating the validity of the cluster solution using variables that were not included in the cluster analysis itself. The first variables that were examined in this regard included demographic and clinical variables. Consistent with the hypothesis, a number of differences among the clusters were present. Specifically, the Impaired group (cluster 2) has a significantly lower Glasgow Score than all other groups. This low score is indicative of a comatose state resulting from a severe head trauma. Thus, it is posited that the level of trauma that would lead to such a low resulting coma score would intuitively result in overall significant neurocognitive impairment.

In considering the age of injury and age at testing, it was hypothesized that for the Impaired group there would be a much shorter duration for the time of injury to time of assessment, as well as an overall younger age of injury, when compared to the other clusters. There was not a statistically significant difference for the duration from injury to assessment. This most likely was because there was a restriction of range, due to the fact that the majority of TBI cases were seen within the same time frame. While the age of the impaired cluster (cluster 2) was lower than the other groups, it was not at a level of statistical significance. However, the Attention group (cluster 3) was significantly older than most groups (with the exception of cluster 4). These findings are consistent with previous studies that suggest that there is a developmental influence on how TBI effects outcome based upon premorbid achievement (Yeats & Taylor, 1997; Ewing-Cobbs, Fletcher, & Levin, 1997; Lord-Maes & Obrzut, 1996; Yeates & Taylor, 1997; Kinsella, Prior, & Sawyer, 1995; Verger, Junqué & Levin, 2001). The average performance on most indices of the TOMAL subtests may be due to the achieved premorbid performance; further, the fact that it was not significantly different from the other cluster with average performance (cluster 4) further supports this contention.

Given that only some of the clusters exhibited the expected pattern of poorest performance on the Digit Symbol/Coding subtest, which has traditionally been identified as the Wechsler test that is most sensitive to TBI, we conducted exploratory analysis to determine if our entire sample exhibited a pattern of performance consistent with this traditional finding. In other words, it may have been that the lack of low performance on Digit Symbol by some of our clusters was due to an atypical pattern of performance in which the entire sample did not exhibit the expected decrement in Digits Symbol performance. Results of these analysis indicated that the present sample's performance was consistent with prior reports in that the lowest performance was obtained on Digit symbol (Coding $M = 6.77$, Vocabulary $M = 7.44$, Block Design $M = 7.57$, Digit Span $M = 8.31$). Furthermore, a repeated measures ANOVA indicated that the differences among the subtests were significant, $F(3{,}423) = 8.13, p < .001$, and post hoc analysis indicated that the Coding subtest was significantly lower than Vocabulary, $t(141) = 1.94, p < .05$, Digit Span, $t(141) = 4.91, p < .001$, and Block Design, $t(141) = 2.34, p < .05$ (one tailed tests). A similar pattern of performance was present when the Index scores were examined on a reduced sample of participants ($n = 137$). Thus, the lack of expected decrements in Coding performance of some of our clusters could not be attributed to atypical performance in our TBI groups as a whole. Rather, the results suggest that while coding performance may be diminished for some individuals who have suffered TBI, this is not a ubiquitous finding, given that some patients perform adequately, relative to the other subtest. Whether these findings generalize to the Processing Speed factor as well remains to be seen, although such a finding would be expected from the current results given the central role of Coding to the measurement of that factor.

With regard to differences in IQ among the clusters, only general differences in level of IQ were hypothesized so that it was predicted that the impaired cluster would show lower overall scores than that of the normal cluster. This prediction was supported as the impaired cluster did perform worse on all IQ subtest scores. However, in addition to overall differences in IQ, a more refined analysis was accomplished that examined the difference between the clusters on the major intellectual domains assessed by the Wechsler scales. It was decided that in order to maximize the number of subjects included in the analysis, subtests rather than index scores would be used as proxy measures for the more comprehensive index scores. Therefore, the Vocabulary subtest selected as the measure of the Verbal Comprehension Index, the Block Design selected as the measure of the Perceptual Organizational Index, Digit Symbol Coding as the Freedom from Distractibility Index, and Digit Span as the Working Memory Index.

The results of these analyses indicated that there were indeed differences among the clusters on the four cognitive domains. To better understand these differences, the cognitive profiles for each of the clusters were described, based upon the four-factor solution discussed earlier (see figure 9). Using this method, the Impaired cluster (C2) shows an overall impairment for each of the domains of verbal, perceptual organizational, freedom from distractibility and working memory. Also consistent with the neurocognitive data, the Average cluster shows average performance, with only a discrepancy between the domains of freedom from distractibility and working memory, with working memory being slightly above average, while freedom from distractibility is slightly at or below average. The Verbal cluster (C5) also shows a similar pattern of performance between the Verbal variable and the Perceptual Organizational variable. However, unlike the neurocognitive data, there is an additional dip in the scores for the Freedom from distractibility item (CD). This would suggest either an additional impairment in Executive function, or a confounding of verbal information in the Coding subtest. The Non-verbal cluster (C1) also shows a corresponding difference between verbal and perceptual organizational tasks (consistent with neurocognitive data), but without any other dissimilarities in performance from the neurocognitive information. Finally, the Attention cluster shows average performance for all domains. This information helps to reinforce the assertion that additional information provided by the cluster solutions for the TOMAL data are elucidating previously undetected deficits in cognitive abilities, in otherwise average looking cases. The results for this study, and the resulting profiles are inconsistent with many studies that find that a specification of only 2 or 3 factors is necessary (Ward, Ryan, & Axelrod, 2000; Donders, J., Tulsky, & Zhu, J., 2001; Taylor, & Heaton, 2001) to provide a significant level of specificity in differentiating patterns of cognitive performance. However, with the exception of the Donders, Tulsky, and Zhu (2001; which used TBI adults) study, those studies are limited to either normal subjects or those subjects whose clinical impairment is other than an injury with such dramatic cognitive implications as TBI holds. Further, these cognitive profiles are consistent with previous studies that support a four-factor solution for intelligence (Ryan & Paolo, 2001), and do include a sample of neurocognitive injury, other clinical participants, and a normative sample. Thus the inclusion of a fourth domain, and moreover a specific extended exploration into more exhaustive tests of cognitive function (such as those of the TOMAL), seems warranted.

When looking at the achievement data, we do not see the clear delineation of clusters that was observed for the neurocognitive data, or that which was partially evident in the IQ data. However, this is not to be completely unexpected. In fact, previous research (Lezak, 2004, p 174-190) has shown that while IQ can be impacted by TBI due to its measurement of aptitude, achievement tests, due to their very nature, should be an indicator of premorbid functioning. Therefore, any differences seen in achievement information would theoretically be more attributable to impairment in the connection cortices to the learned information.

For the behavioral data, it should first be noted that due to the fact that severity of TBI often limits the child's ability to attend school. It must therefore be noted that while the results did show statistically significant differences for the parent's and self report data, the teacher's report forms may be of limited interpretability due to the limited sample size (n = 55). However, not withstanding these limitations, some interesting information about the composition of the clusters is available. The most striking is evident in the self-report forms. While they were initially thought to be of limited usefulness (Weis & Smenner, 2007), they provided insight into the reported difficulties of some the TBI patient. The Non-Verbal cluster (C1) reported a greater amount of thoughts and behaviors consistent with clinical maladjustment than behaviors and thoughts consistent with school maladjustment. However, this group also reported a higher number of thoughts and behaviors that are consistent with school maladjustment than those associated with personal maladjustment. Further, the Average cluster (C4) reported fewer thoughts and behaviors that would be associated with clinical and school maladjustment, but reported a disproportionately greater number of thoughts and behaviors that are associated with personal maladjustment. However, while validity of the clinical and personal maladjustment composites have been demonstrated (Weiss & Smenner, 2007), little is known about the validity of the school maladjustment composite. Finally, one should consider that this is the first study to examine possible patterns of behavioral differences between homogeneous subgroups indentified using neuropsychological testing procedures.

Finally, the clinical data provided some important considerations, especially with regard to making treatment recommendations, recommendations for school interventions, as well as providing a prognosis for potential sparing and recovery. The results regarding severity of injury (based upon GCS), in conjunction with the information reported using the BASC should provide valuable information for consideration in treatment planning and prognosis. While the Impaired cluster does seem to have the lowest GCS score (thus indicating a severe head injury), one should expect a severe impairment of global abilities. Further, those clinicians faced with TBI patients who have seemingly average performance on tests of intelligence should not ignore the potential impairment of more specific domains of cognition. More specifically, as seen in the Attention cluster, while most functioning was seemingly at or near average performance, there was a significant decrement in the Attention/Concentration task. This would suggest that impairment may exist and could go undetected thus yielding potential problems at school and home. The potential to leave problems untreated is further evidenced when considering the BASC results. While the Average cluster, seemed to remain unimpaired in all areas of IQ and Neurocognitive functioning, they reported a very high number of thoughts and behaviors that could, left untreated, result in problematic behavior at school and home.

While great planning went into this study, there are considerations to be made as to its limitations. One of the major limitations of this study lies in the subject of study. While the study had set out to incorporate the support of a large amount of supporting collateral information (such as IQ, achievement, and behavioral data), it was limited by its ability to incorporate complete sets of data for all cases. Due to the potential severity of injury when collecting data from individuals with a TBI, it can be impossible to collect certain data points. The question must then be asked as to how to interpret such missing data. For this study, all efforts were made to use procedures that would maximize the amount of data available for analysis, while at the same time trying to minimize the potential for Type I error.

However, given the above limitations and caveats, this data set is one of a magnitude not before used in a cluster analysis for neurocognitive data, and therefore should provide a solid foundation for future studies attempting to identify homogenous subgroups of TBI or other neurocognitive impairments.

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TABLES

Table 1

Demographic and clinical data for the entire sample ($N = 187$).

TOMAL Scores	Mean	SD
Age (years)	12.3	3.7
Age when Injured	11.3	3.7
Months since Injury	12.2	15.5
GLASGOW (n = 127)	6.9	3.0
	n	%
Gender		
Female	77	41.2
Male	110	58.8
Ethnicity ($n = 128$)		
Caucasian	72	56.3
African American	30	23.4
Hispanic	22	17.2
Asian-American	1	0.8
Other	3	2.3
Secondary Diagnosis		
ADHD	1	0.5
Seizure	1	0.5
Other	5	2.7
Learning disability	1	0.5
No secondary diagnosis	179	95.8

TBI Type		
Open	15	8.0
Closed	172	92.0
Mode of Injury (n = 186)		
Motor Vehicle Accident	100	53.5
Restrained	50	50.0
Unrestrained	27	27.0
Not applicable	19	19.0
Pedestrian versus Motor Vehicle	39	20.9
Gunshot	9	4.8
Fall	5	2.7
4-Wheeler Accident	10	5.3
Bike Accident	4	2.1
Skiing	9	4.8
Other	10	5.3

Table 2

Test of Learning and Memory (TOMAL) subtest and Index scores for the entire sample (*N* = 187).

TOMAL Scores	Mean	SD
Subtests		
TMFS	8.0	3.0
TWSR	7.8	3.4
TOR	5.9	3.3
TDF	6.8	2.7
TPR	7.6	3.8
TLF	6.7	2.7
TDB	8.3	2.3
TLB	8.0	2.6
TFM	7.5	2.9
TVSR	6.6	3.3
TAVM	7.4	3.5
TVSM	8.3	2.6
TMFL	7.7	4.2
TMI	9.7	2.4
TMFSD	6.5	3.3
TFMD	8.8	2.4
TWSRD	7.7	3.0
TVSRD	8.4	2.3

Index Scores		
TVMI	80.6	16.2
TNMI	82.8	15.2
TCMI	81.1	14.7
TDRI	85.6	13.0
TACI	83.2	13.5
TSRI	82.4	13.7
TFRI	80.7	16.8
TARI	86.8	17.3
TLI	79.6	17.9

Note. TMFS = Memory for Stories, TWSR = Word Selective Reminding, TOR = Object Recall, TDF = Digits Forward, TPR = Paired Recall, TLF = Letters Forward, TDB = Digits Backwards, TLB = Letters Backwards, TFM = Facial Memory, TVSR = Visual Selective Reminding, TAVM = Abstract Visual Memory, TVSM = Visual Selective Reminding, TMFL = Memory for Location, TMI = Manual Imitation, TMFSD = Memory for Stories Delayed, TFMD = Facial Memory Delayed, TWSRD= Word Selective Reminding Delayed, TVSRD = Visual Selective Reminding Delayed, TVMI = Visual Memory Index, TNMI = Non-Verbal Memory Index, TCMI = Composite Memory Index, TDRI = Delayed Recall Index, TACI = Attention/Concentration Index, TSRI = Selective Recall Index, TFRI = Free Recall Index, TARI = Associative Recall Index, TLI = Learning Index.

Table 3

3-Cluster Solution for TOMAL Data.

TOMAL Subtest	C1 Mean	C1 SD	C2 Mean	C2 SD	C3 Mean	C3 SD
TMFS	7.4	2.4	5.3	1.8	10.2	2.3
TWSR	7.1	2.7	4.6	2.6	10.4	2.4
TOR	5.1	2.1	2.8	2.0	8.6	2.9
TDF	6.8	2.4	5.3	2.5	7.7	2.8
TPR	7.2	3.5	3.9	2.9	10.2	2.5
TLF	6.7	2.4	4.9	2.5	7.9	2.4
TDB	7.8	1.8	7.0	2.3	9.7	2.1
TLB	7.8	2.1	6.1	2.2	9.3	2.4
TFM	6.7	2.9	6.1	2.3	9.2	2.5
TVSR	6.3	3.1	4.7	2.8	8.0	3.0
TAVM	6.8	3.4	5.2	3.0	9.4	2.7
TVSM	7.8	2.7	6.8	2.1	9.7	2.1
TMFL	7.4	3.6	4.3	2.9	10.0	4.0
TMFSD	9.7	1.2	9.5	6.4	9.8	2.2
TFMD	5.7	2.6	3.5	1.8	9.2	2.4
TWSRD	8.2	2.7	8.3	1.7	9.8	2.1
TVSRD	7.3	2.7	4.9	2.4	9.8	1.7

Note. See table 2 for explanation of abbreviations.

Table 4

4-Cluster Solution for TOMAL Data.

TOMAL	C1		C2		C3		C4	
Subtest	Mean	SD	Mean	SD	Mean	SD	Mean	SD
TMFS	8.3	2.0	5.3	1.8	10.2	2.3	6.9	2.4
TWSR	8.2	3.2	4.6	2.6	10.4	2.4	6.6	2.2
TOR	4.7	2.1	2.8	2.0	8.6	2.9	5.3	2.1
TDF	6.6	2.3	5.3	2.5	7.7	2.8	7.0	2.4
TPR	8.8	3.0	3.9	2.9	10.2	2.5	6.3	3.4
TLF	6.2	2.7	4.9	2.5	7.9	2.4	7.0	2.3
TDB	7.8	2.0	7.0	2.3	9.7	2.1	7.8	1.7
TLB	6.9	2.3	6.1	2.2	9.3	2.4	8.3	1.8
TFM	6.5	2.6	6.1	2.3	9.2	2.5	6.8	3.0
TVSR	5.8	3.0	4.7	2.8	8.0	3.0	6.5	3.2
TAVM	3.6	2.0	5.2	3.0	9.4	2.7	8.6	2.6
TVSM	8.0	2.6	6.8	2.1	9.7	2.1	7.8	2.8
TMFL	4.4	2.6	4.3	2.9	10.0	4.0	9.1	2.9
TMFSD	10.3	1.2	9.5	6.4	9.8	2.2	9.0	1.0
TFMD	7.2	1.9	3.5	1.8	9.2	2.4	4.9	2.7
TWSRD	8.0	2.7	8.3	1.7	9.8	2.1	8.3	2.7
TVSRD	8.0	2.6	4.9	2.4	9.8	1.7	6.8	2.7

Note. See table 2 for explanation of abbreviations.

Table 5

5-Cluster Solution for TOMAL Data.

Subtest	Non-Verbal		Impaired		Att./Conc.		Average		Verbal	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
TMFS	8.3	2.0	5.3	1.8	11.2	2.1	9.3	2.2	6.9	2.4
TWSR	8.2	3.2	4.6	2.6	10.8	2.9	10.0	1.8	6.6	2.2
TOR	4.7	2.1	2.8	2.0	8.5	3.0	8.6	2.8	5.3	2.1
TDF	6.6	2.3	5.3	2.5	6.3	2.3	8.9	2.7	7.0	2.4
TPR	8.8	3.0	3.9	2.9	9.9	2.3	10.5	2.6	6.3	3.4
TLF	6.2	2.7	4.9	2.5	6.5	1.8	9.1	2.3	7.0	2.3
TDB	7.8	2.0	7.0	2.3	8.7	1.7	10.5	2.2	7.8	1.7
TLB	6.9	2.3	6.1	2.2	8.4	1.6	10.1	2.8	8.3	1.8
TFM	6.5	2.6	6.1	2.3	9.4	2.5	9.1	2.5	6.8	3.0
TVSR	5.8	3.0	4.7	2.8	7.5	3.0	8.5	2.9	6.5	3.2
TAVM	3.6	2.0	5.2	3.0	9.5	2.5	9.3	3.0	8.6	2.6
TVSM	8.0	2.6	6.8	2.1	9.3	1.9	10.1	2.3	7.8	2.8
TMFL	4.4	2.6	4.3	2.9	7.3	3.1	12.6	2.8	9.1	2.9
TMFSD	7.2	1.9	3.5	1.8	10.1	2.0	8.3	2.4	4.9	2.7
TFMD	8.0	2.7	8.3	1.7	9.3	2.5	10.2	1.6	8.3	2.7
TWSRD	8.0	2.6	4.9	2.4	9.7	1.9	10.0	1.5	6.8	2.7
TVSRD	7.6	1.9	7.0	2.3	9.3	1.9	9.9	1.4	8.2	2.6

Note. See table 2 for explanation of abbreviations.

Table 6

3-Cluster Discriminant Function Analysis Classification Results.

Original	Ward's Method	Predicted Group Membership			
		1	2	3	Total
Count	1	61	5	5	71
	2	5	39	0	44
	3	2	0	70	72
%	1	85.9	7.0	7.0	100.0
	2	11.4	88.6	.0	100.0
	3	2.8	.0	97.2	100.0

Note. 90.9% of original grouped cases correctly classified.

Table 7

4-Cluster Discriminant Function Analysis Classification Results.

Original	Ward's Method	Predicted Group Membership				
		1	2	3	4	Total
Count	1	22	1	1	1	25
	2	1	41	0	2	44
	3	1	0	67	4	72
	4	2	0	3	41	46
%	1	88.0	4.0	4.0	4.0	100.0
	2	2.3	93.2	.0	4.5	100.0
	3	1.4	.0	93.1	5.6	100.0
	4	4.3	.0	6.5	89.1	100.0

Note. 91.4% of original grouped cases correctly classified.

Table 8

5-Cluster Discriminant Function Analysis Classification Results.

Original	Ward's Method	Predicted Group Membership					
		1	2	3	4	5	Total
Count	1	22	1	1	1	0	25
	2	1	40	0	0	3	44
	3	1	0	33	1	0	35
	4	0	0	3	32	2	37
	5	2	1	2	2	39	46
%	1	88.0	4.0	4.0	4.0	.0	100.0
	2	2.3	90.9	.0	.0	6.8	100.0
	3	2.9	.0	94.3	2.9	.0	100.0
	4	.0	.0	8.1	86.5	5.4	100.0
	5	4.3	2.2	4.3	4.3	84.8	100.0

Note. 88.8% of original grouped cases correctly classified.

Table 9

Cross-Tabulation for Ward's Method and K-mean's Iterations: 5-Cluster Solution.

Ward's Method		K-Means Iteration 1	2	3	4	5	Total
1	Count	19	3	2	0	1	25
	Ward's Method	76.0%	12.0%	8.0%	.0%	4.0%	100.0%
2	Count	1	39	0	0	4	44
	Ward's Method	2.3%	88.6%	.0%	.0%	9.1%	100.0%
3	Count	1	0	31	3	0	35
	Ward's Method	2.9%	.0%	88.6%	8.6%	.0%	100.0%
4	Count	0	0	2	32	3	37
	Ward's Method	.0%	.0%	5.4%	86.5%	8.1%	100.0%
5	Count	5	5	0	1	35	46
	Ward's Method	10.9%	10.9%	.0%	2.2%	76.1%	100.0%
Total	Count	26	47	35	36	43	187
	% of Total	13.9%	25.1%	18.7%	19.3%	23.0%	100.0%

Note. Kappa = .79, N = 187, T = 21.32, $p < .001$

Table 10

Cross-Tabulation for Ward's Method and K-mean's Iterations: 4-Cluster solution.

Ward's Method		K-Means Iteration 1	2	3	4	Total
1	Count	19	5	0	1	25
	Ward's Method	76.0%	20.0%	.0%	4.0%	100.0%
2	Count	1	40	0	3	44
	Ward's Method	2.3%	90.9%	.0%	6.8%	100.0%
3	Count	9	0	59	4	72
	Ward's Method	12.5%	.0%	81.9%	5.6%	100.0%
4	Count	4	5	2	35	46
	Ward's Method	8.7%	10.9%	4.3%	76.1%	100.0%
Total	Count	33	50	61	43	187
	% of Total	17.6%	26.7%	32.6%	23.0%	100.0%

Note. Kappa = .75, N = 187, T = 17.44, $p < .001$

Table 11

Cross-Tabulation for Ward's Method and K-mean's Iterations: 3-Cluster solution.

Ward's Method		K-means Iteration 1	2	3	Total
1	Count	57	8	6	71
	Ward's Method	80.3%	11.3%	8.5%	100.0%
2	Count	10	34	0	44
	Ward's Method	22.7%	77.3%	.0%	100.0%
3	Count	3	0	69	72
	Ward's Method	4.2%	.0%	95.8%	100.0%
Total	Count	70	42	75	187
	% of Total	37.4%	22.5%	40.1%	100.0%

Note. Kappa = .79, N = 187, T = 14.81, $p < .001$ confirming the null hypothesis.

Table 12

Descriptive statistics for demographic and clinical variables for the 5-Cluster Solution (N=187).

	Cluster				
Variable	1	2	3	4	5
Gender					
Male	15	25	20	22	28
Female	10	19	15	15	18
Ethnicity					
Caucasian	10	18	16	13	15
African American	5	5	3	4	13
Hispanic	3	5	4	4	6
Asian American	0	0	0	0	1
Other	0	0	0	0	1
Age at Time of Injury					
Mean	12.1	10.6	10.0	13.3	10.9
SD	3.3	4.0	3.3	3.6	3.6
N	25	44	35	36	45
Age in Years					
Mean	13.1	11.7	11.1	14.2	11.7
SD	3.4	3.8	2.9	3.7	3.6

N	25	44	35	37	46
GCS					
Mean Score	6.4	5.9	8.3	7.4	6.7
SD	3.1	2.4	3.0	3.7	2.8
N	19	30	25	18	29

Note. GCS = Glasgow Coma Scale

Table 13

Rotated component matrix for Wechsler four-factor principal components analysis.

	Component			
Wechsler Subtests	1	2	3	4
Vocabulary (VO)	**0.81**	0.27	0.02	0.22
Comprehension (CO)	**0.81**	0.15	0.21	-0.03
Similarities (SM)	**0.81**	0.18	0.16	0.09
Information (IN)	**0.81**	0.28	0.07	0.14
Arithmetic (AR)	**0.67**	0.16	0.24	0.37
Object Assembly (OA)	0.20	**0.84**	0.12	0.03
Picture Arrangement (PA)	0.09	**0.74**	0.23	0.33
Block Design (BD)	0.35	**0.66**	0.24	0.20
Picture Completion (PC)	0.46	**0.66**	0.06	-0.06
Coding (CD)	0.15	0.12	**0.90**	0.06
Symbol Search (SS)	0.19	0.31	**0.76**	0.25
Digit Span (DS)	0.22	0.18	0.19	**0.88**
Eigen values	5.75	1.42	1.05	0.74
Percent Variance	47.92	11.80	8.77	6.17

Table 14

Descriptive statistics for IQ variable for 5-cluster solution.

Wechsler	Non-Verbal		Impaired		Att./Conc.		Average		Verbal	
Subtest	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
VO	6.58	3.13	5.15	2.13	8.73	2.16	10.20	3.08	6.71	2.80
BD	5.63	4.02	4.19	2.91	8.50	3.54	10.04	2.35	8.51	2.91
CD	6.21	3.58	3.81	3.11	8.87	2.57	7.96	3.71	6.73	2.70
DS	7.53	2.48	6.11	2.45	8.53	2.16	11.24	2.37	8.17	2.42

Note. VO = Vocabulary, BD = Block Design, CD = Coding, DS = Digit Span.

Table 15

Descriptive statistics for Woodcock-Johnson variables for 5-cluster solution.

WJ3	Non-Verbal		Impaired		Att./Conc.		Average		Verbal	
Scores	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
WJ3WS	85.83	25.2	78.0	20.1	110.0	18.92	95.8	24.4	93.3	11.5
WJ3BR	88.83	12.7	77.6	10.2	99.0	11.12	93.5	12.7	85.8	14.7
WJ3BM	89.67	16.6	83.3	9.7	103.5	8.94	98.0	13.4	90.9	6.3

Note. WJ3WS = Writing Skills, WJ3BR = Broad Reading, WJBM = Broad Math

FIGURES

Figure 1. Long-Term Memory Model.

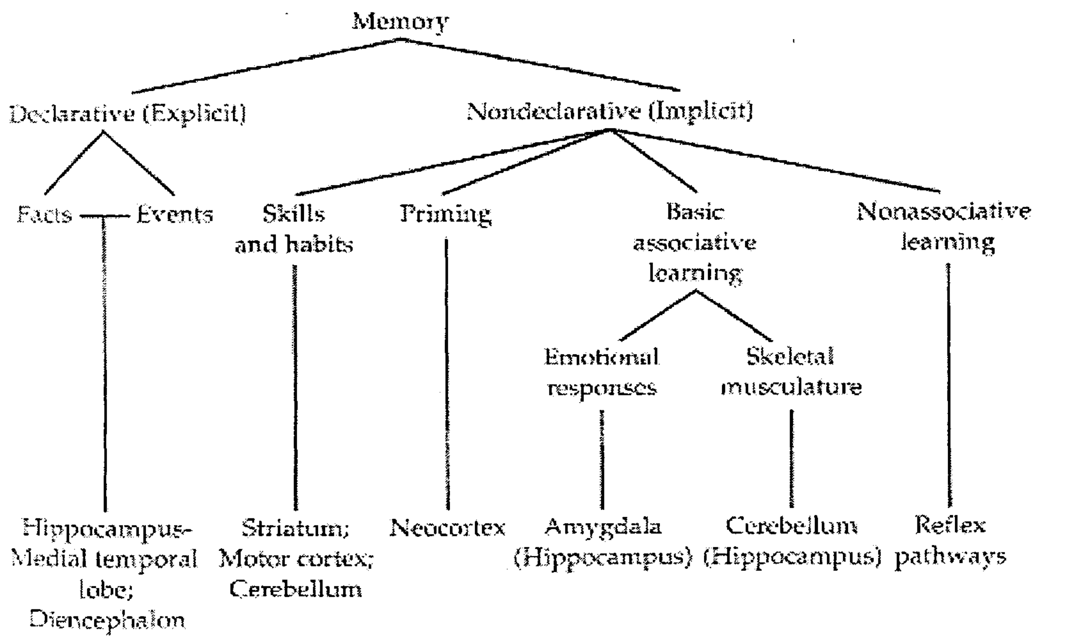


Figure 2. Profile of TOMAL Subtest Scores for the 5-Cluster Solution.

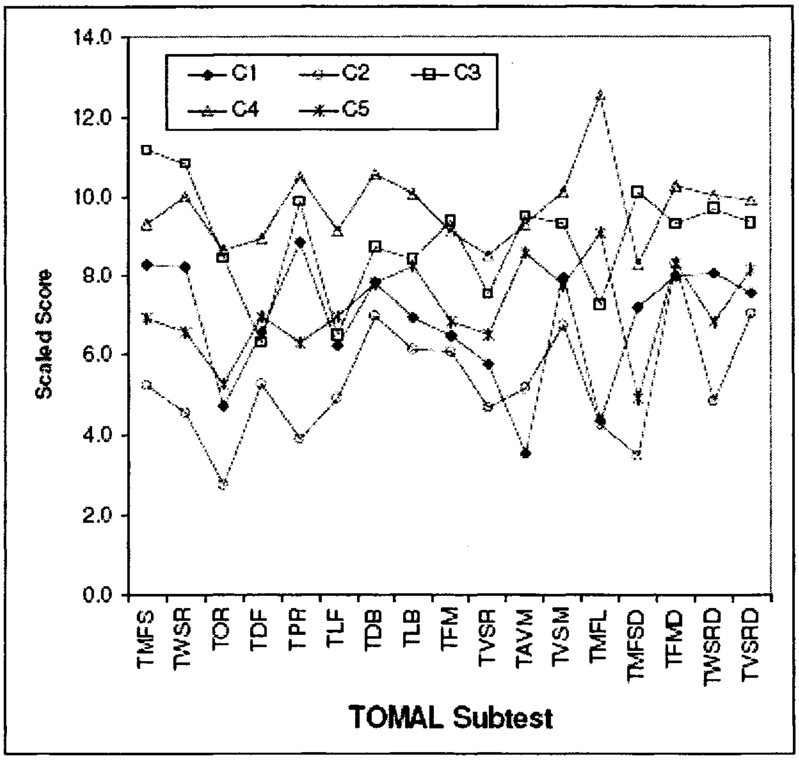
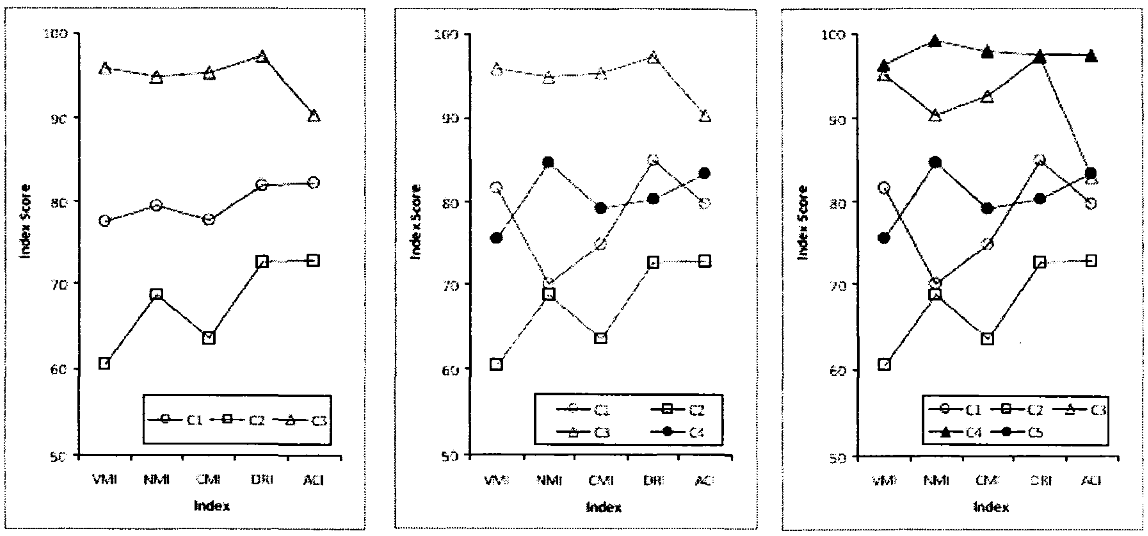


Figure 3. Cluster Profiles of TOMAL Indices for Three, Four and Five Cluster Solutions: Ward's Method



Note. VMI = Verbal Memory Index, NMI = Non-verbal Memory Index, CMI = Composite Memory Index, DRI = Delayed Memory Index, ACI = Attention/Concentration Index.

Figure 4. 3-Cluster Discriminant Function Analysis

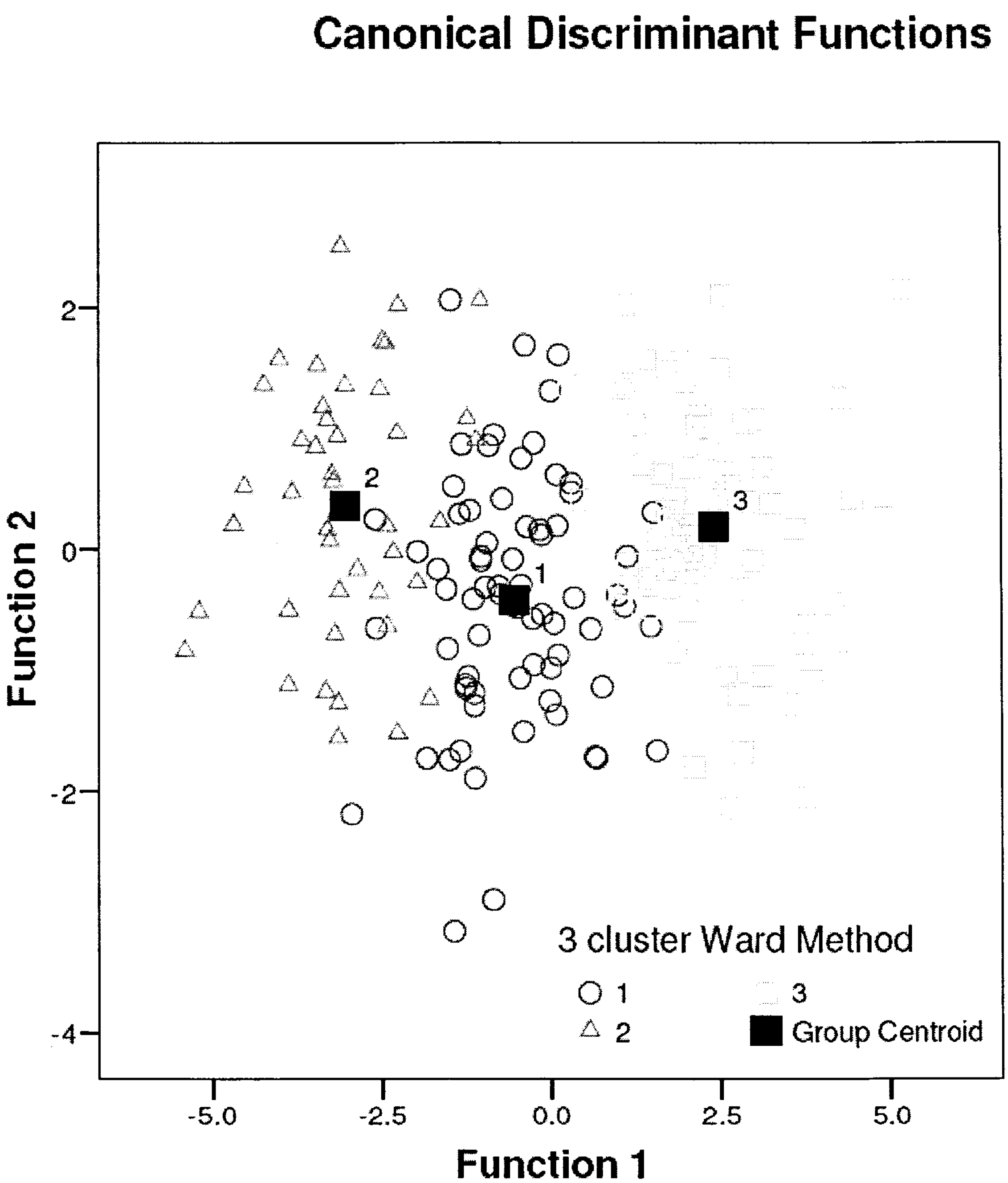


Figure 5. 4-Cluster Discriminant Function Analysis

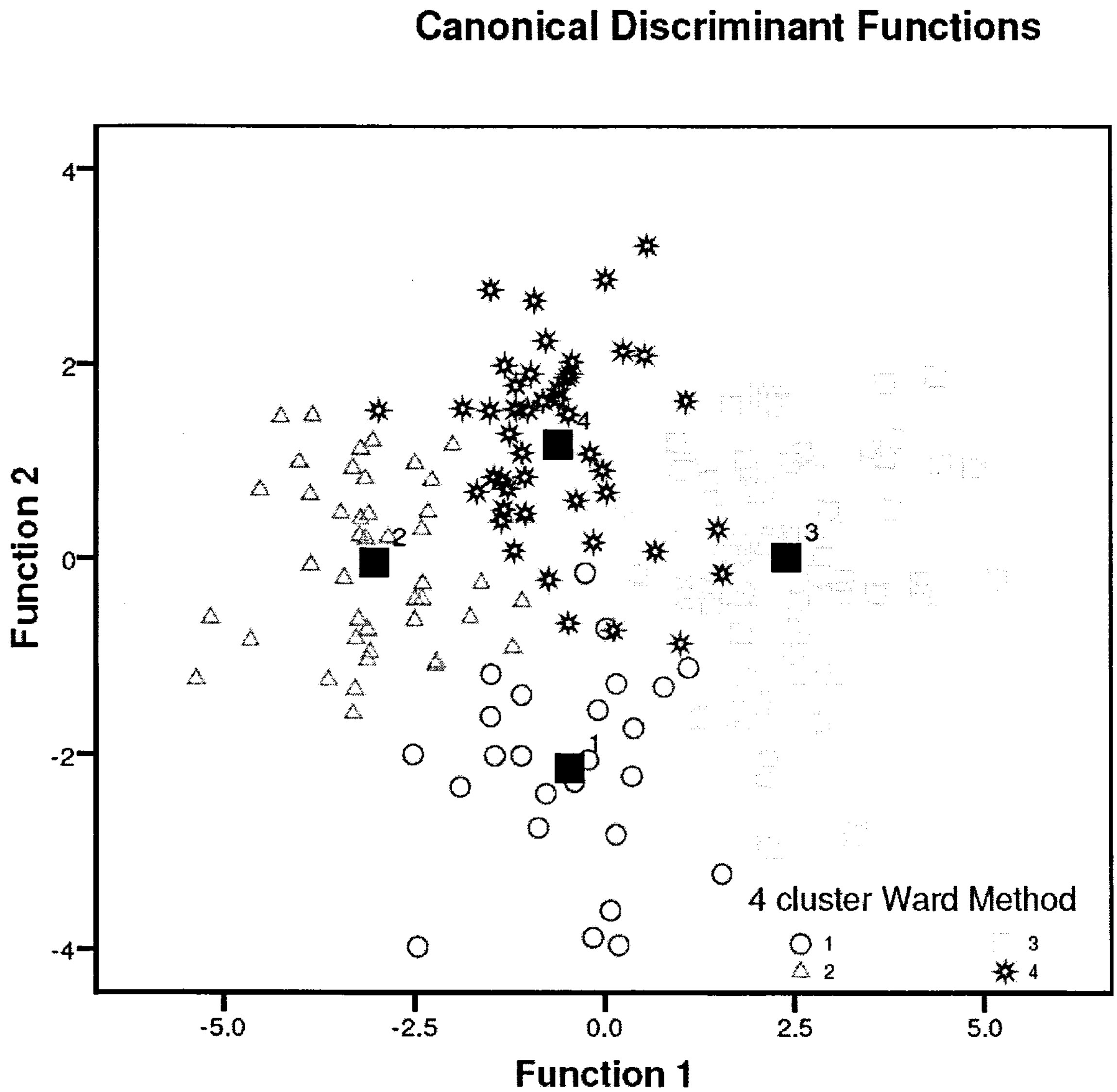


Figure 6. 5-Cluster Discriminant Function Analysis

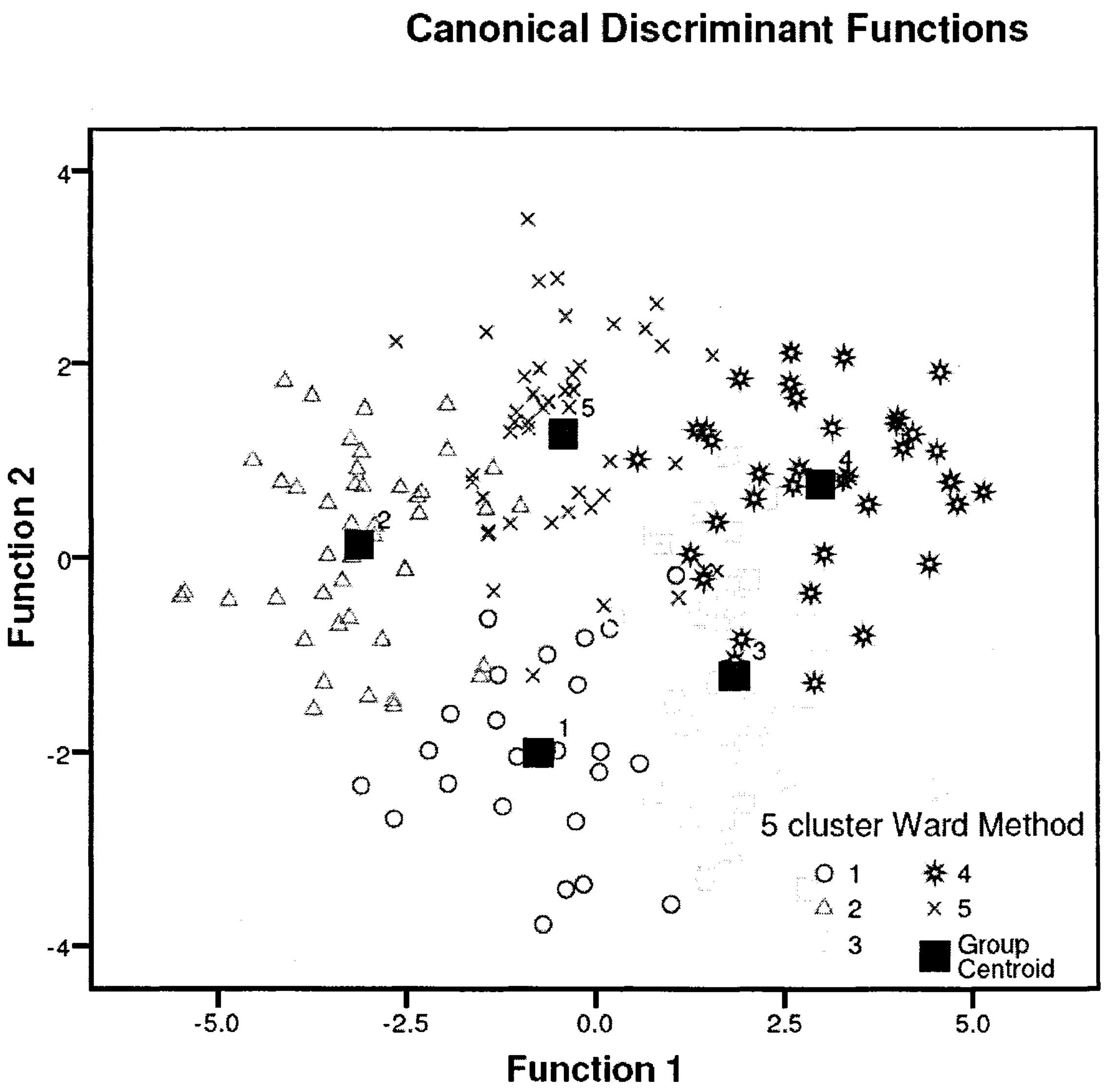


Figure 7. Differences in Age of Onset and Time to Testing for 5-Cluster Solution

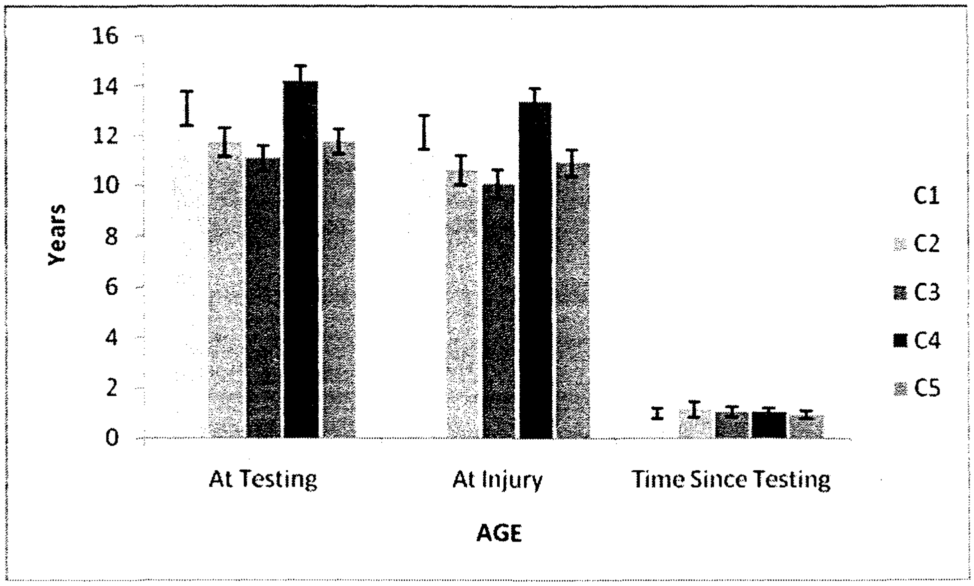


Figure 8. Glasgow Coma Scores for 5-Cluster solution.

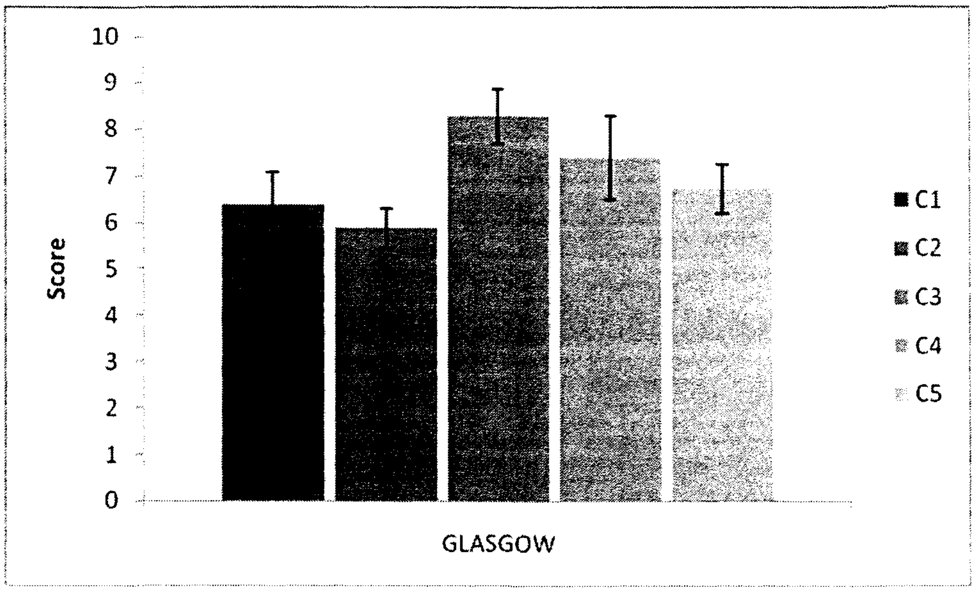


Figure 9. IQ Profiles for the 5-Cluster Solution.

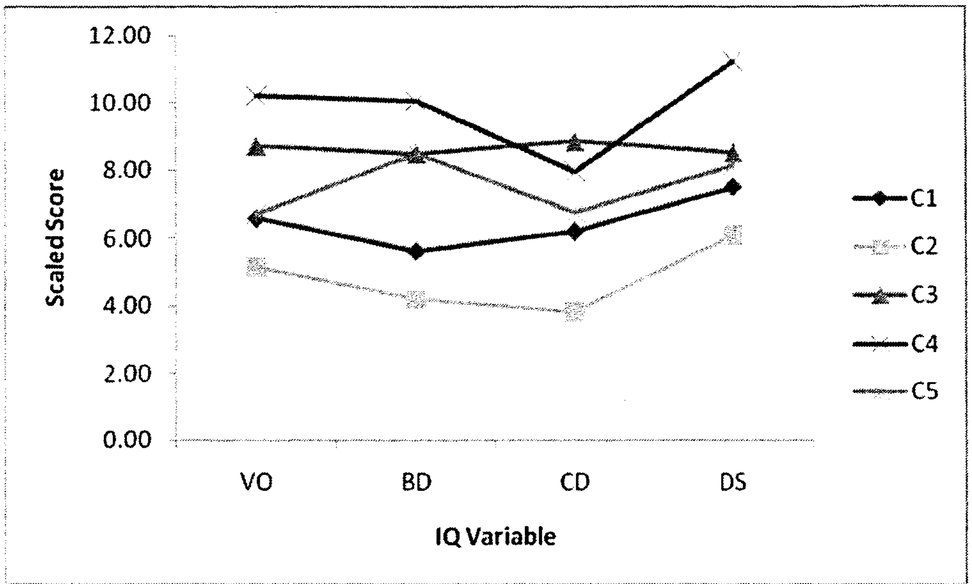


Figure 10. BASC Parent-Report Composite Scores

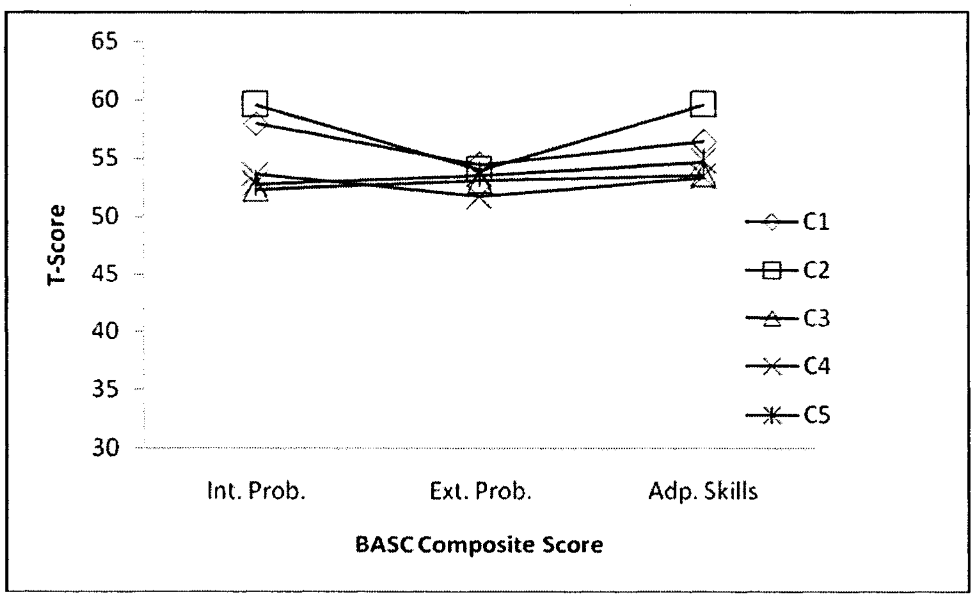


Figure 11. BASC Teacher Composite Scores

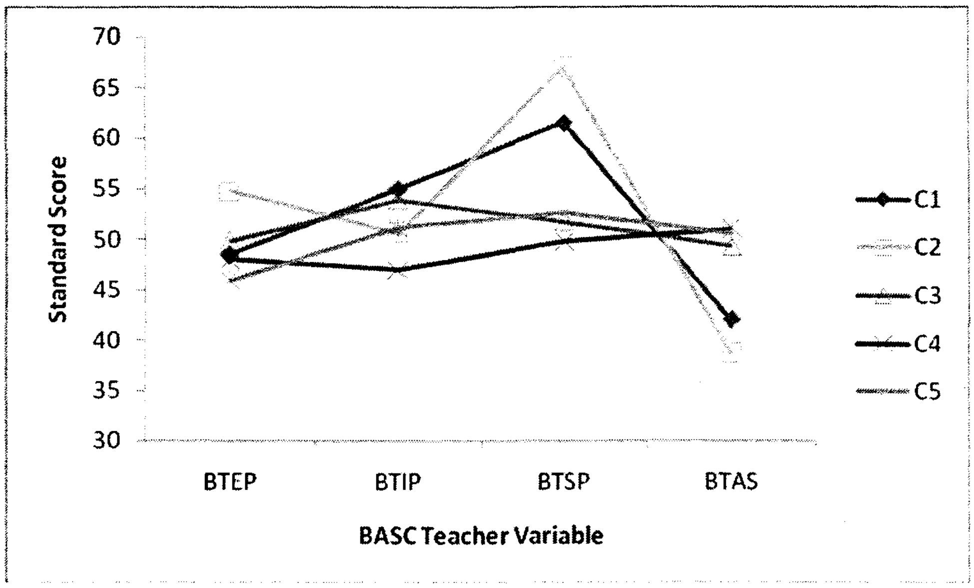
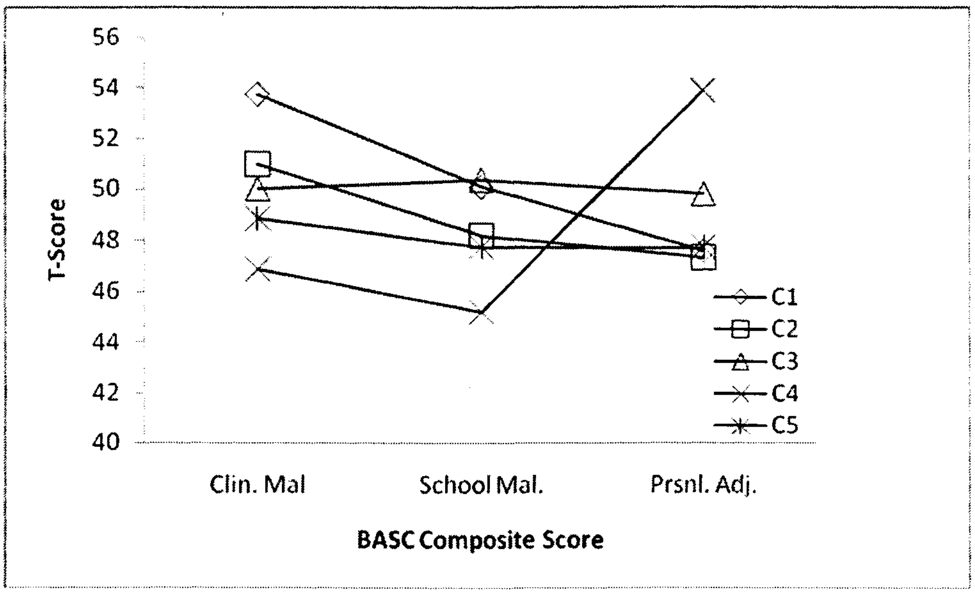


Figure 12. BASC Self-Report Composite Scores



VITA

Graduate College
University of Nevada, Las Vegas

Brian D. Leany

Home Address:
2962 Juniper Hills Dr #101
Las Vegas, NV 89142

Degrees:
Bachelor's of Arts, Psychology
San Diego State University, 2001

Thesis Title: Parsing Neurocognitive Heterogeneity in Pediatric Traumatic Brain Injury

Thesis Committee:
Chairperson, Dr. Daniel Allen, Ph.D.
Committee Member, Dr. Christopher Heavey, Ph.D.
Committee Member, Dr. Bradley Donohue, Ph.D.
Graduate Faculty Representative, Dr. Chad Cross, Ph.D.