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Executive function profiles in pediatric traumatic brain injury

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EXECUTIVE FUNCTION PROFILES IN PEDIATRIC TRAUMATIC BRAIN INJURY

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ABSTRACT

Executive Function Profiles in Pediatric Traumatic Brain Injury

by

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Traumatic brain injury is a common cause of disability and death among children in the United States. Insult to the frontal and temporal lobes are frequent in closed head brain injury. Cognitive deficits in a variety of domains are common sequelae of brain trauma. In many cases, trauma to the frontal and temporal lobe regions engender prominent deficits in higher-order cognitive processing, memory, and attention.

Higher-order cognitive processing, or Executive Functions are the grouping of cognitive processes necessary for organization of thoughts and activities, attending to the activities, prioritizing tasks, managing time efficiently, and making decisions (Alvarez & Emory, 2006; Jurado & Rosselli, 2007; Miyake et al., 2000). Due to the complexity and heterogeneity of the executive functioning construct, researchers often conceptualize the multiple functions into executive subprocesses (Alvarez & Emory, 2006; Goldberg et al., 2003; Goldberg & Weinberger, 2004; Jurado & Rosselli, 2007; Miyake et al., 2000; Stuss & Alexander, 2000; Zelazo et al., 1997) including, but not limited to shifting, updating, inhibition, cognitive flexibility, problem-solving, response maintenance, goal-formation, planning, task-analysis, and even working memory. Despite the importance of the frontal lobes in regulating cognitive abilities, many of their functions are still not well understood.

Examination of specific executive subprocesses between healthy individuals and those who have sustained a traumatic brain injury (TBI) would provide insight into the function of executive subprocesses, how they manifest in healthy controls, and importantly, how they are disturbed by brain injury. Notwithstanding, identifying the neurocognitive profiles associated with certain executive subprocesses may better help medical professionals to classify and treat subtypes of childhood TBI.

Tasks that assess executive subprocesses have existed for many years, with one of the oldest and most well studied task being the Trail Making Test (TMT; Reitan, 1986; Reitan & Wolfson, 1993; U.S. Army Individual Test Battery, 1944). The Trail Making Test assesses different aspects of executive functioning including, scanning, visuo-motor, spatial skills, tracking, planning, shifting, divided attention, inhibition, and cognitive flexibility ability. With over 60-years of use, the psychometric properties of the TMT have been well established, and it has been shown to be sensitive to both acquired and neurodevelopmental forms of brain damage (Moll, Oliveira-Souza, Moll, Bramati, & Andreiuolo, 2002; Reitan, 1955; Reynolds, 2002; Wiegner & Donders, 1999; Sánchez-Cubillo et al., 2009; Zakzanis, Mraz, & Graham, 2005). While sensitive to the biological integrity of the frontal lobes, tasks such as the TMT also appear sensitive to lesions in other brain regions (Demakis, 2004; Stuss, et al., 2001).

In recent years, a number of alternate versions of the TMT have been developed, with one notable example being the Comprehensive Trail Making Test (CTMT; Reynolds 2002). The CTMT was designed to provide an expanded assessment of the executive functions assessed by its predecessor, and is purported to assess decision-making, planning, inhibition, sequencing, development of actions, and motor outputs. Like the

TMT, initial validity evidence supports the sensitivity of the CTMT to brain injury (Allen, Haderlie, Kazakov, & Mayfield, 2009; Armstrong, Allen, Donohue, & Mayfield, 2007; Orem, Petrac, & Bedwell, 2008). In addition, the CTMT provides norms based on a large standardization sample (N = 1769) ranging in age from 8 to 89-years of age, that is stratified by age, gender, ethnicity, and geographic region. In order to be representative of the United States population, CTMT norms are based on the 2000 census data.

Based on these considerations, the current study will investigate executive subprocess performance as assessed by the Comprehensive Trail Making Test (CTMT) in 242 children and adolescents, including 121 with TBI, and 121 matched normal controls. The present study will use cluster analysis of CTMT scores to determine whether 1) discrete executive function subgroups of children with TBI can be identified and 2) whether these TBI subgroups differ in executive function profiles from normal children. Results are anticipated to advance understanding of TBI heterogeneity in executive function ability, as assessed by the CTMT. It is also hoped that results from this study provide insight into higher-order cognitive processing in children, such that results may assist in short- and long-term treatment of childhood TBI.

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CHAPTER 1

REVIEW OF RELATED LITERATURE

Traumatic Brain Injury (TBI) is a major cause of death in children and adolescents in the United States and other developed nations (Burns & Hauser, 2003), such that approximately half of a million cases of TBI are reported in children under the age of 15, each year (Langlois, Rutland-Brown, & Wald, 2006). Of those cases, seventy- to ninety-percent are classified as mild, ten- to twenty-percent require hospitalization, ten-percent will live with permanent disabilities, and an estimated one-percent will not survive (Kirkwood, et al., 2008; Ornstein, et al., 2009; Ruthland-Brown, Langlois, Thomas, & Xi, 2006). Lifetime costs for children and adolescents who have sustained a TBI are estimated to be around four million dollars per individual. Similarly, direct and indirect costs associated with TBI in the United States are reported to exceed $80 billion, annually (Langlois, Rutland-Brown, & Wald, 2006).

The neuropsychological basis of brain injury should first be addressed in the context of the neuropathology. Based on results of brain damage via contact and acceleration/deceleration forces, TBI has been associated with both focal and diffuse injuries. Specifically, the ventral and polar frontal and temporal regions of the brain often endure excessive tissue strain and shearing against the ridges and confines of the anterior and middle fossa (Levine, Katz, Dade, & Black, 2002), which accounts for the common observation of memory, attention and executive function deficits in children with TBI. The extent of brain injury and resulting neurocognitive deficits are also influenced by factors such as open or closed head injury, and location of insult (Reitan & Wolfson,

1993; Schutzman & Greenes, 2001). While the primary insults of TBI are critical to address, secondary brain injury, such as ischemia, cerebral hypoxia, hypotension, brain edema, changes in cerebral blood flow, increased intracranial pressure, along with cognitive and behavioral deficits may occur within minutes, hours, or days of the accident; secondary injury have been shown to intensify the rate of disability and even mortality (Gabriel, Ghajar, Jagoda, Pons, Scalea, & Walters, 2002). Moreover, time elapse between primary trauma and initial medical attention, length of coma, and neurological presentation are factors that influence the outcome of secondary brain injury (Reitan & Wolfson, 1993; Schutzman & Greenes, 2001). Neuronal shearing in close proximity to the hippocampal, entorhinal, and perirhinal regions of the temporal lobe have been associated with memory deficits (Barbas & Blatt, 1995). Given that these regions are strongly connected to the limbic pathways, as well as the orbital and ventromedial frontal cortices, abnormal behavioral manifestations following to TBI, are likely to occur. These primary and secondary factors interact to produce heterogeneous neurocognitive outcomes for children who sustain TBI.

Neurocognitive deficits are common following TBI and often conform to a 'dose response effect,' in that TBI severity is strongly associated with the severity of cognitive and behavioral impairments (Anderson et al., 2001; Anderson, Catroppa, Morse, Haritou, & Rosenfeld, 2005; Anderson Catroppa, Rosenfeld, Haritou, & Morse, 2000; Donders, 1993; Max et al., 2004; Miller & Donders, 2003; Rohling, Meyers, & Millis, 2003). There is also a substantial degree of heterogeneity with regard to neurocognitive outcomes following a TBI (Jaffe et al., 1995; Millis et al., 2001). Heterogeneous

outcomes have been found in a number of domain, such as memory (Alexander & Mayfield, 2005; Allen et al., 2010; Anderson & Catroppa, 2007; Babikian & Asarnow, 2009; Crosson, Novack, Rrenerry, & Craig, 1989; Farmer et al., 1999; Gillespie, Bowen, & Foster, 2006; Lowther & Mayfield, 2004; Shum, Harris, & O'Gorman, 2000; Thaler et al., 2010), attention (Allen et al., 2010; Anderson & Catroppa, 2005; Babikian & Asarnow, 2009; Chan et al., 2003; Thaler, Allen, Reynolds, & Mayfield, 2010; Yeates et al., 2005), and executive function (Anderson & Catroppa, 2005; Donders 1995, 1996, 1999; Greve et al., 2002; Muscara, Catroppa, & Anderson, 2008; Nadebaum, Anderson, & Catroppa, 2007; Slomine et al., 2002).

For the more commonly occurring neurocognitive deficits, one would anticipate varying level of cognitive impairment among individuals, and these variations may be useful in understanding injury severity and in identifying subgroups within heterogeneous populations. A number of cluster analytic studies provided evidence for subgroups based on cognitive function.

For example, in a recent study Allen and colleagues (2010) found significant differences between children with TBI (N=150) and healthy controls (N=150) in memory and attention profiles. Cluster analysis indicated that a five-cluster solution most appropriately characterized the TBI group, while a four-cluster solution was most appropriate for controls. Furthermore, while the TBI clusters were differentiated by both level and pattern of performance differences across memory and attention abilities, the control group clusters were primarily differentiated by level of performance. For the TBI groups, the lowest scoring cluster exhibited a relative increase on delayed recall and

attentional/concentration indices, a middle cluster showed a relatively lower score on the visual memory index, and an average cluster that exhibited adequate performance on the nonverbal memory index. Additionally, the analysis characterized verbal and visual clusters, indicating relative increases on the nonverbal and attention/concentration indices, and relative decreases on the nonverbal and attention/concentration indices, respectively (Allen et al., 2010). Additional literature on childhood TBI supports the aforementioned findings of heterogeneous cognitive and behavioral profiles (Donders, 1996, 1999, 2008, Donders & Warschausky, 1997; Donders, Zhu, & Tulksy, 2001; Mottram & Donders, 2006; Wiegner & Donders, 1999). Such profiles also appear to discriminate between trajectories of recovery in TBI.

In a separate study, Mottram & Donders (2006) examined the presence of profile subtypes on the California Verbal Learning Test-Children's Version (CVLT-C; Delis, Kramer, Kaplan, & Ober, 1994) in 175 children with TBI. Cluster analysis indicated that a four-cluster solution most appropriately represented performance in this sample. Specifically, three of the clusters were distinguishable based on level of performance, while the fourth cluster differed in patter of performance. The fourth cluster had a higher amount of inaccurate recall responses. Interestingly, the two clusters representing highest level of performance also performed significantly better on the Wechsler Intelligence Scale for Children-Third Edition Revised (WISC-III; Wechsler, 1991). As a whole, children with more severe TBI performed worse on the assessments, which suggested that both the CVLT and WISC-III were sensitive to TBI subtypes. Using cluster analytic techniques, a number of studies indicate specific domains to be sensitive to TBI, such as

intelligence, verbal learning, and memory. However, a paucity of literature exists regarding cluster analytic work with measures of executive subprocessing.

Cluster Analytic Studies of Executive Functions

Donders & Storm (1995) analyzed the Intermediate version of the Halstead Category Test (IHCT) to identify distinct pattern of performances on sample of 87 children with TBI. A four-cluster solution emerged with differential level and pattern of performance. All clusters were distinguishable based on level of IHCT subtest performance to the extent that clusters two and four performed well, albeit different, while cluster one and three performed poorly. Differences in performance also presented as performance on Subtest III, IV, and V varied in pattern between clusters.

In a separate study, Donders (1998) examined profile subtypes of 920 children, 320 of them between the ages of 5 and 8 years old, and the rest between 9 and 16 years old, on the Children's Category Test (CCT). The CCT is a test of abstraction and problem solving abilities and because of this has been considered a test of executive functions. Separate cluster analyses of the younger and older children's CCT scores demonstrated variable level and patterns of performance across subtests and age groups on the CCT. A three-cluster solution was identified in the younger children, with two of the clusters differentiating by level of performance, and the third cluster representing selective impairment on the specific color, oddity in shape or size, and missing color subtests. On the other hand, a four–cluster solution was identified for the older children. Two of the clusters differentiated by level of performance, such that one had low numbers of errors on subtests three through six, whereas cluster two had a high number

of errors on those subtests. Clusters three and four had nearly the same number of total errors, but could be differentiated on pattern of performance across the subtests. Donders (1998) indicated that it could not be determined whether differences in the number of clusters identified for younger and older children resulted from actual differences in age associated expression of executive subprocessing ability or whether differences emerged by using different forms of the assessment. Donders (1998) concluded that age, and thus developmental integrity, was an important variable to consider when interpreting CCT performance. More specifically, clusters with the older average age performed better than did the clusters with the younger average age, a finding that exemplifies the importance of considering level and pattern of performance across the lifespan. Such findings draw relevance to the use of age matching between patients and control groups.

Based on theses studies, one would anticipate that differences among individuals with TBI would also occur in the domain of executive function. Given the likelihood of deficits in this area, it is somewhat surprising that few studies have examined the heterogeneity of executive subprocessing abilities in childhood TBI. Thus, motivation for the current study was based on recognizing the paucity of literature in this area of research, as well as the importance of understanding higher-order cognitive function in children after sustaining a brain injury. In the following sections we review executive function and numerous subprocesses to provide a basis for the current work.

Executive Function as a Cognitive Construct

Although the extent to which the frontal lobes are involved in the regulation of behavior has only recently become understood, the indications of their importance have long been present in the literature. Quite possibly the earliest and most famous case study providing insight into the importance of the frontal lobes was that of Phineas Gage. In 1848, Phineas Gage (Harlow, 1848; Macmillian, 1986; Collidge & Wynn, 2001) suffered an unfortunate accident in the workplace, where a 13¼-pound iron tamping rod was dropped onto a dynamite charge and subsequently propelled upwards through the left side of his face, only to exit through the dorsal region of his cranium (Coolidge & Wynn, 2001), destroying a portion of his left frontal and temporal lobe (Macmillian, 1986). Although he survived, he was unable to return to work on the railroad construction crew because of deficits in attention, planning, and organization. He also experienced significant changes in his personality and behavior (Harlow, 1868). Harlow's (1868) description of Mr. Gage's dysfunctional behavior may have been the first documented literature on executive processing (Coolidge & Wynn, 2001). Much later, the Russian psychologist and physician A.R. Luria wrote extensively about behavior and cognitive abilities moderated by the frontal lobe. Luria (1966) suggested that individuals with frontal lobe damage experienced difficulties in complex psychological activities, such as task evaluation, as well as completing complex, purposive, and goal-directed task. More recent literature has suggested that damage to the frontal lobe results in emotional dysregulation, as well as deficits in many executive subprocesses, such as visual-spatial search abilities, inhibition, decision-making operations, planning, sustained attention, and

set-maintenance (Clark, Manes, Antoun, Sahakian, & Robbins, 2003; Stuss et al., 2000; Wozniak et al., 2007).

Based on the work of Luria (1966) and others, researchers have attempted to generate an operational definition to explain executive functioning. For instance, Lezak (1982) who may have originated the term "executive function," suggested that executive processes require "socially useful, personally enhancing, constructive, and creative abilities" (p. 281). Welsh and Pennington (1988) expanded on this definition by suggesting that executive functions bestow an individual with skills needed to problem solve, maintain a set of strategies, and attend to future goals. Other researchers define executive functions as an individual's capacity for decision making, planning, inhibition, sequencing, development of plan and action, and motor outputs (Reynolds & Horton, 2008). Pennington and Ozonoff (1996) suggested that executive functions were distinct from other cognitive domains. From this work it is apparent that executive function is a multidimensional construct, and further that its various subprocesses are subsumed by distinct brain regions and neural circuits. Neuropsychological and neuroimaging studies support this suggestion and indicate that executive functions might best be viewed as consisting of multiple subprocesses and that the frontal lobes have substantial more interconnectivity with subcortical regions of the brain than any other lobe or cortex (Alvarez & Emory, 2006; Coolidge & Wynn, 2001; Goldberg et al., 2003; Goldberg & Weinberger, 2004; Jurado & Rosselli, 2007; Konishi et al., 1998; Miyake et al., 2000; Zelazo et al., 1997).

With regard to executive subprocesses, Miyake et al., (2000) described *set-shifting* as the executive subprocess requiring a participant to shift between mental sets or between sets of stimuli that are disparate semantically, symbolically, or topographically. The shifting process also involves the disengagement of an irrelevant task set and successive active engagement of a relevant task set (Miyake, et al., 2000). The Wisconsin Card Sorting Test, plus-minus task, number-letter task, and the global-local task among others, are tests purported to measure executive set-shifting abilities. As an example of this type of task, the WCST requires sorting cards on the basis of three concepts, either color, shape, or number. After a participant has successfully sorted 10 cards consecutively according to one concept, the sorting rule changes and he or she must shift mental-sets to sort one of the other concepts (Heaton, 1993). Multiple studies using fMRI- and event-related potentials (ERP) of these types of card sorting tasks have found strong associations between executive set-shifting abilities and brain activation in the lateral and medial prefrontal cortices, mid-dorsolateral and mid-ventrolateral prefrontal cortices, as well as the bioccipital and parietal regions of the brain (Barcelo, 2003; Barcelo, Escera, Corral, & Perianes, 2006; Monchi, Petrides, Petre, Worsley & Dagher, 2001; Moulden et al., 1998; Rubia et al., 2006).

Executive *inhibition* is the ability to deliberately withhold prepotent responses, inhibit or stop ongoing response, and resist distraction by competing events or responses (Barkley, 1997). The Stroop task, antisaccade task, stop-signal task, and go/no go tasks have been suggested as measures of executive inhibition (Kiefer, Marzinzik, Weisbrod, Scherg, & Soutzer, 1998; Miyake et al., 2000; Salthouse et al., 2003), as these tasks

require an individual to deliberately withholding automatic responses. Inhibition is evident in Stroop tasks, wherein participants are presented with words of various color names (e.g., red, blue, green) that are printed in different colored ink. Subjects are required to name the color of ink that is printed while ignoring the word itself. Stroop tasks require the subject to inhibit or override the tendency to report a more dominate response (i.e., reading the color word). Neuroimaging studies suggest that Stroop tasks activate left dorsolateral and inferior frontotemporoparietal, as well as right frontal and parietal cortices, right medial frontal region, and right supramarginal region of the brain (Langenecker & Nielson, 2003; Rubia et al., 2006). Similarly, selective motor inhibition relies on motor outputs to assist in the cessation of habitual responses and stopping or altering the motor activity of cognitively complex event. Executive motor response inhibition has been associated with the right orbital and mesial prefrontal cortex, right middle and inferior frontal gyri, frontal limbic area, anterior insula, and inferior parietal lobe (Garavan, Ross, & Stein, 1999; Rubia et al., 2006).

The *updating* subprocess is closely associated with working memory and requires the ability to monitor incoming information for relevance and then appropriately revise the item (Miyake et al., 2000). Updating requires an individual to actively manipulate relevant information in working memory, rather than passively store information (Miyake et al., 2000). The keep-track, letter-memory, and the *N*-back task purport to measure executive updating abilities. Despite their differences, these tasks require participants to closely monitor numbers, words, or objects presented as stimuli. The tests also require participants to update their cognitive representation for appropriate categories subsequent

to new stimuli being presented. The medial orbitofrontal, prefrontal, dorsolateral, and superior parietal cortices of the brain have been associated with the updating executive subprocess (Lie, Specht, Marshall, & Fink, 2006; Rose, Simonotto, & Ebmeier, 2006; Smith & Jonides, 1999).

The *decision-making* subprocess is related to response uncertainty and has shown increased activating when an individual is required to evaluate the reward and punishment potential of an event. The decision-making subprocess may also require emotional processing (Clark et al., 2003). The various neuropsychological based gambling tasks have been purported to measure decision-making abilities. Gambling tasks assess an individual's ability to make real-life decisions based on monetary compensation and probabilistic decision. In one study, Manes and colleagues (2002) found that participants with dorsomedial and dorsolateral lesions performed poorer than normal controls on tasks requiring decision-making abilities. A similar study also found decision-making deficits in participants with bilateral lesions of the ventromedial prefrontal cortex (Bachara et al., 2001). Decision-making has shown specific association with the left middle occipital gyrus and frontal gyrus, as well as the right orbitofrontal cortex, insula, superior frontal cortex, and frontal gyrus (Weber & Huettel, 2008).

The executive ability of *planning* involves delineation, organization, and interaction of behaviors to conceptualize change, respond objectively, generate and select alternative actions, coordinate mental functioning, and hold information to eventually facilitate action (Culbertson & Zillmer, 1998; Boghi et al., 2006). The Six Element Test, Self-ordered pointing task, Tower of London, Tower of Hanoi, and Hotel Test have been

suggested as measures of executive planning. The tower task requires a participant to construct different problem configurations in as few moves as possible, while adhering to strict guidelines. Participants move only one object at a time and cannot place more objects on a peg than it accommodates. Neuroimaging studies suggest that such planning tasks activate the fronto-thalamic gating system, dorsolateral prefrontal cortex, superior and right frontal gyrus, caudate nucleus, putamen, and the cerebellum (Lazeron, Rombouts, Scheltens, Polman, & Barkhof, 2004).

Complex executive *sequencing*, also referred to as cognitive flexibility, involves the ability to sequence information in a specific order, such as sequencing numbers in order or completing tasks in succession. Neuropsychological assessments which purport to examine an individual's ability to sequence information are script, picture, and action-sequencing tasks. In general, these tasks require an individual to arrange a set of cards which depict an event, in correct temporal order. The executive sequencing subprocess has been associated with bilateral activation of the mesial, orbital, and dorsolateral regions of the brain (Wildgruber, Kischka, Ackermann, Klose, & Grodd, 1999). In recent studies, researchers have shown that sequencing errors are associated with age-related changes (Allain et al., 2007).

Summary and Hypotheses

Based on the supporting literature, it is clear that variations in level and pattern of performance exist across a multitude of cognitive domains. The executive function domain is of great importance, as it mediates higher-order cognitive function. While variations in both level and pattern of performance have been partially attributed to

common fluctuations in the general population, brain injury must be recognized as a contributing factor. Variations in cognitive performance which exceed performance by individuals in the general population may, at least impart, be attributable to brain injury. Thus, based on the validity of its predecessor, and due to the fact that decision-making, planning, inhibition, and other executive subprocesses are often disrupted in TBI cases, the CTMT may be useful for identifying subtypes of TBI of cognitive performance in children. TBI subtypes defined by differing patterns of impairment on executive function tasks may in turn prove useful in understanding outcomes of cognitive functioning following brain injury. Such pursuits have significant neuropsychological, interventional, rehabilitation, and education implications. Specific analyses were conducted to determine whether differing levels and patterns of executive abilities would evidence in a child sample with TBI, in comparison to an age- and gender-matched HC group, selected from the CTMT standardization sample. Based on prior studies examining executive subprocess impairment in TBI cases (Muscara, Catroppa, & Anderson, 2008; Nadebaum, Anderson, & Catroppa, 2007; Ornstein et al. 2009), along with prior cluster studies (Allen et al., 2010; Donders & Strom, 1995; Wiegner & Donders, 1999), it was hypothesized that at least three clusters would be evident in the childhood TBI group which could be differentiated by level of performance (e.g., average, low, and impaired) on the CTMT. Four- and five-cluster solutions were also examined, since studies of other abilities (e.g., memory, intelligence) provide some support for these more complex solutions (Allen et al., 2010; Thaler et al., 2010). To provide a basis for comparison, similar analyses were conducted with an age-and gender-matched HC sample selected

from the CTMT standardization sample. For the HC group, it was hypothesized that a four-cluster solution would be evident which could be differentiated by level of performance (e.g., superior, above-average, average, and low) on the CTMT. Three- and five-cluster solutions would be examined to ensure proper identification of the optimal cluster solution. It was expected that performance by the TBI group would be characterized by more variability among CTMT trials than the HC group. Secondly, it was hypothesized that the clusters identified in the TBI group would be associated with important clinical, cognitive, and behavioral variables, including intelligence, academic achievement, memory, attention, receptive and expressive language, and motor abilities, as well as behavior. Specifically, the more severely impaired TBI cluster would also exhibit the poorest performance on outcome variables across these domains. If the initial cluster analytic procedure is unable to differentiate between two cluster solutions, examining the association between cluster solution and outcome measure performance may help determine the optimal cluster.

CHAPTER 2

METHODOLOGY

Participants

Participants included 242 children and adolescents between the ages of 8 and 19 years. Of these, 121 had sustained a traumatic brain injury (TBI group). Individuals making up the TBI group were included if they had completed the CTMT as part of their routine neuropsychological evaluation, and had evidence of structural brain damage based on comprehensive neurological evaluation, and did not have pre-injury neurological or neurodevelopmental disorders, such as a learning disability or Attention Deficit Hyperactivity Disorder (ADHD).

Evidence of brain damage resulting from TBI was established in all cases using appropriate neuroimaging, laboratory, and examinational findings. Glasgow Coma Scale (GSC) scores were available for 80 of the participants and indicated that on average, injuries were severe in nature (Mean = 6; SD = 3). The GCS was completed by first responders at the scene of the accident or in the emergency room when the patient had been transported from the accident scene. Of the 121 participants selected, 62.0% were Caucasian, 17.4% were Hispanic, 11.6% were African American, 1.7% were Asian American, and 7.4% were either Other or unaccounted for. The sample was 63.6% male with an average age of 14.6 years (SD = 2.7) and 84.2% of the sample was right hand dominate. Neuropsychological evaluation occurred from 5 to 115 weeks following TBI (Mean = 18.8; SD = 22.0). Eleven (9.1%) participants sustained open head injuries, while the others sustained closed head injuries. Participants sustained their injuries in the

following ways: motor vehicle accident (43.8%), pedestrian struck by a motor vehicle (13.2%), 4-wheeler accident (9.9%), fall (9.1%), gunshot wound (5.8%), bicycle accident (0.8%), skiing accident (0.8%) and other (4.1%).

The healthy control (HC) group included 121 children will be selected from the CTMT standardization sample to match the TBI group on age and gender. Cases will be matched individually, and when more than one member of the standardization sample matched a TBI participant on age and gender, random selection will be used to choose the individual selected from the HC group.

Measures

Overview of the Comprehensive Trail Making Test (CTMT; Reynolds, 2002)

The CTMT is an adaptation of the Trail Making Test (TMT), which is a neuropsychological test with a long history of use in both children and adults. The TMT was originally developed in 1938 as a test of "divided attention" and intellectual functioning (Partington & Leiter, 1949). It was later incorporated into the U.S. Army Individual Test Battery (1944) where it received its current name, the Trail Making Test (TMT)., and subsequently into the Halstead-Reitan Neuropsychological Test Battery (HRNB) (Reitan, 1986; Reitan & Wolfson, 1995; Reitan & Wolfson, 1993). The TMT is divided into two parts, A and B. Part A of the test requires the examinee to connect numbered circles (1 to 25) in order. With increased difficulty, Part B instructs the examinee to connect numbers (1 to 13) and letters (A to L) in alternating sequence (Reitan and Wolfson, 1995). The TMT continues to be among the most often used neuropsychological tests in clinical and research settings (Rabin, Barr, & Burton, 2005)

because it has repeatedly displayed its sensitivity to brain function in children and adults (Jaffe et al., 1993; Reitan, 1955, 1958, 1971). It has also helped validate the neuroanatomical correlates of executive subprocesses (Moll, Oliveria-Souza, Moll, Bramati, & Andreiuolo, 2002; Zakzanis, Mraz, & Graham, 2005), and is recognized as a measures of visual searching abilities, perceptual/motor speed, processing speed, and working memory (Reynolds, 2002; Sánchez-Cubilloet al., 2009).

Although having a number of positive features, the TMT also has a number of limitations, including the absence of adequate normative information. The CTMT was designed to address limitations of the TMT and provide an expanded assessment of the executive functions assessed by its predecessor. It is purported to assess decision-making, planning, inhibition, sequencing, development of actions, and motor outputs. The CTMT contains five Trials, as opposed to two found in the TMT. The additional Trails aim to increase the reliability, validity, and sensitivity to brain malfunction, as well as to isolate executive subprocesses mediated by the frontal lobes. Additionally, the normative information is available based on a large standardization sample that ranges in age from 8 years 0 months to 89 years 0 months (Moses, 2004; Reynolds, 2002). The CTMT purposefully employed visual scanning, visual search, sequencing skills, cognitive flexibility, attention, and set-shifting processes, as they are essential components of daily functioning. The CTMT is based on empirical and theoretical models of functional neuroanatomy in humans (Reynolds, 2002). Thus, assessing human brain development, maturation, and age associated decline, as measured by performance on the CTMT may

help us to understand the lifelong trajectories of executive function (Moses, 2004; Reynolds, 2002).

CTMT Description

The CTMT contains three sample Trails (A, B, and C) as well as five timed Trails. Initially Sample A is administered. Sample A is a simplification of CTMT Trails 2 and 3. The half-page sample requires the examinee to draw a line connecting the encircled numbers, 1 through 5, in ascending order while avoiding six empty distractor circles. If only Sample A is completed, participants may only complete Trails 1, 2, and 3. Trial 1 of the CTMT is inherently similar to Part A of the original TMT. During this Trail, the participant is instructed to draw a line connecting ordered numbers 1 though 25. Each number is contained in a plain black circle, for all five trials. Instructions for Trial 2 require the examinee to draw a line connecting the numbers 1 thought 25, except this time, he or she must avoid twenty-nine empty distractor circles. Trial 3 of the measure instructs the examinee to draw a line connecting numbers 1 through 25. Thirteen empty distractor circles and 19 distractor circle containing irrelevant line drawings are present in Trial 3 of the CTMT. Trails 2 and 3 are similar to Part A of the original TMT, insofar as the numbered circles still need to be connected in a numerically ascending fashion. In this case, the distractor circles add a unique inhibition and attentional component (Moses, 2004; Reynolds, 2002).

Sample B is given to the examinee prior to Trail 4 of the CTMT. This sample presents as a half-page paper with encircled numbers 1 through 5, three rectangles with English language numbers (e.g., four) and two empty distractor circles. In this sample,

participants are directed to draw a continuous line from the number-filled-circles to the rectangles, connecting the numbers, in ascending order. Only if the participant completes Sample Trail B can she or he proceed to Trail 4 of the CTMT. Trail 4 requires examinees to draw a line connecting the numbers 1 through 20. In this Trail, 11 of the numbers are presented as Arabic numeral (e.g., 1, 7) and the remaining nine are spelled out in English (e.g., nine). This trial purports to enrich the reliability component set-shifting, one validated executive function subprocesses (Moses, 2004; Reynolds, 2002).

Sample C is a simplified version of the TMT Part B and CTMT Trial 5. In this sample, the examiner instructs the participant to draw a continuous line connecting numbers 1 though 9 and letters A though D in alternating sequencing. Only when Sample C is complete, can Trail 5 of the CTMT be administered to the participant. Trial 5 requires examinees to draw a line connecting numbers 1 through 13 and letters A though L, in alternating sequence (i.e., 1-A-2-B-etc.). Fifteen empty distractor circles appear on the same page as Trial 5. Errors within a Trail are defined by marking a number or letter out of sequence. And, while errors are not directly accounted during scoring procedures, they may be used during the qualitative interpretation (Moses, 2004; Reynolds, 2002).

CTMT Administration and Scoring

The CTMT typically takes 5-12 minutes to administer. The CTMT is administered in a controlled, comfortable, and low-distraction environment, with minimal noise and adequate lighting. The examinee is provided a smooth and flat surface, as well as several sharpened pencils without erasers to compete the tasks. The examiner uses a

stopwatch to record the time of each Trail. And, of great importance, the five Trails of the CTMT must be completed by the examinee in numerical order. The completion time of each Trail is recorded, in seconds, by the examinee, directly into the CTMT Record Booklet. Based on the subjects' age, his or her raw scores can be converted to standardized *T*-scores and Percentile Ranks. Summing the *T*-scores from Trails 1 though 5, an examiner can establish a Composite Index, Quotient, z-Score, or Stanines. Section III allows for *T*-scores and the Composite Index to be potted thus, providing the examiner with a graphical representation of CTMT performance. Section IV provides direction about calculating the mean trail score for each trail completed by the examinee. The section also provides scores at the $p = 0.05$ and $p = 0.01$ confidence intervals to determine significance (Moses, 2004; Reynolds, 2002).

CTMT Validity

In order for a test to demonstrate validity, scores must appropriately and accurately pertain to the performance and interpretation of the test; a measure must be supported theoretically and empirically. The content validity of the CTMT is supported through theoretical, as well as empirical evidence from neurobiological and neuropsychological models of executive functioning. While the CTMT shows promise as a tool for assessing executive subprocess abilities, tests of validity are sparse (Moses, 2004; Reynolds, 2002, 2004).

Armstrong and colleagues (2007) examined the validity of the CTMT in 30 adolescents with TBI and 30 non-brain injured normal controls (M =15) years. Adolescents with TBI performed nearly two standard deviations below the comparison

sample mean, and CTMT scores were correlated with injury severity. Receiver Operating Characteristic (ROC) analysis indicated that CTMT adequately distinguished between the TBI group and normal controls. These results indicated that the CTMT, like its predecessor, is sensitive to TBI, supporting the criterion validity of the CTMT.

Smith and colleagues (2008) examined the convergent and divergent validity of the CTMT in 55 healthy undergraduate control participants and 19 community participants requiring neuropsychological evaluation. Results from the study suggested that the CTMT may demonstrate validity for assessing visuospatial processing accuracy and speed, and that the CTMT scores were sensitive to clinical diagnosis (Smith et al., 2008).

Most recently, Allen and colleagues (2009) examined the convergent and discriminant validity of the CTMT in 50 normal children and adolescents and 50 with traumatic brain injury. In terms of the convergent validity, the CTMT factor scores evidenced a significant correlation with tests of perceptual organizational ability, processing speed, sustained attention, and motor function. Additionally, scores on the CTMT exhibited lower correlations with the Verbal Index of the Wechsler scales and Broad Reading score of the Woodcock-Johnson- Third Edition (WJ-III) and higher scores with Academic Skills on the WJ-III, Grooved Pegboard Test, findings which elucidate the discriminant validity of the CTMT (Allen, Haderlie, Kazakov, & Mayfield, 2009). Taken together, CTMT has adequate levels of convergent, divergent, construct, and discriminant validity, which appear to be specific for measurement of executive function subprocesses.

CTMT Reliability

CTMT internal consistency reliability was determined using alternate form reliability estimations, since they appear most sensitive to speeded tests such as the CTMT. In this sense, two equivalent forms of the CTMT were devised and administered to participants. Thereafter, age effects were controlled for by converting all raw score values to T-score equivalents. Subsequently, correlational values were calculated between each of the five CTMT trials. The authors determined that internal consistency values for the five CTMT trials met or exceeded coefficients of .70. Reliability values for the CTMT Composite Index score was determined to be .92 (Reynolds, 2002, 2004). To measure test-retest reliability, 30 adults ranging in age from 20 to 57 years, from Austin, Texas, were tested twice, with a 1-week period between testing. Stability coefficients were established by test-retest reliability and showed to range between .70 and .78 for the five trials of the CTMT. A measure with high test-retest reliability is expected to have only minimal fluctuations in performance across subsequent administrations of the same individual. Test-retest reliability helps to measure the stability of an individual's performance, constructs of interest over time, and errors in assessment due to time sampling. Lastly, scorer reliability coefficients are suggested to range between .96 and .98. (Moses, 2004; Reynolds, 2002, 2004). All participants in the current study were administered all five trials of the CTMT.

Demographic and Clinical Measures

In addition to demographic variables, severity of injury was measured by the Glasgow Coma Scale (GSC; Teasdale & Jennett, 1974). TBI severity was categorized by

mild (13-15), moderate (9-12), or severe (3-8), with scores of 8 or less indicating a comatose state (Teasdale & Jennett, 1974; Jennett & Teasdale, 1981). The time interval between injury and assessment was used as an indicator of recovery, with a longer interval indicating more recovery.

Intellectual, Achievement, Behavioral, Learning and Memory, and Neurocognitive Measures

Wechsler Intelligence Scales (WIS). The Wechsler Intelligence Scales (WIS) were used to assess intellectual functioning. Some participants were administered the Wechsler Intelligence Scale for Children – Third Edition (n = 2) (WISC-III; Wechsler, 1991), some the Wechsler Intelligence Scale for Children – Fourth Edition (n = 68) (WISC-IV; Wechsler, 2003), and others the Wechsler Adult Intelligence Scale – Third Edition (n = 28) (WAIS-III; Wechsler, 1997). Given that these versions of the Wechsler scales share many common subtests, and that these subtests are designed to measure similar abilities across age groups, data were combined across the various versions. We analyzed individual subtests that have been shown in previous research (Reynolds & Ford, 1994) to be strong measures of their representative index, including the Vocabulary (Verbal Comprehension Index), Block Design (Perceptual Organization Index), and Digit Symbol/Coding (Processing Speed Index) subtests. Group differences on the Full Scale IQ for the WIS were also examined. Data was available for 98 of the participants.

The *Reynolds Intellectual Assessment Scale* (RIAS; Reynolds, Kamphaus, 2003). The RIAS is a test of intelligence and memory, designed to assess an individual's verbal and nonverbal intellectual functioning. The RIAS consists of six subtests, four of which

assess intellectual abilities, and two which examine memory ability. In this study, 46 participants completed the RIAS. Recently Allen and colleagues (2010) compared performance on the RIAS to performance on the WISC-III and WISC-IV, in a sample of children and adolescents with TBI. Results from that study indicated that performance on the RIAS was similar to that reported by the WISC-III and WISC-IV. Such findings support the construct validity of the verbal and nonverbal indices, as well as the measure of full scale intellectual functioning (Allen et al., in press). Hence, in the current study, the RIAS verbal and nonverbal indexes, and the WIS verbal and nonverbal indexes will be combined to reflect verbal and nonverbal intelligence.

The Woodcock-Johnson Psycho-Educational Battery Tests of Achievement (Woodcock & Johnson, 1989). Academic achievement was evaluated using the Third version of the Woodcock-Johnson Psycho-Educational Battery Tests of Achievement. Broad Reading and Broad Math cluster scores were selected for analysis as these were completed by most subjects and reflect two of the major components assessed by the tests. These cluster scores have a mean of 100 and a standard deviation of 15. Data was available for 116 of the participants.

Behavioral Assessment System for Children (BASC; Reynolds & Kamphaus, 1992) and the *Behavioral Assessment System for Children, Second Editions* (BASC-2; Reynolds & Kamphaus, 2004). The BASC and BASC-2 are reliable and valid multi-method reports which examine behavior and self-perception on numerous domains. Both reports are divided into the Parent Rating Scale (PRS), Self-Report of Personality (SRP), and Teacher Rating Scale (TRS) and are used to examine adaptive behavior, as well as

externalizing and internalizing concerns. The PRS and TRS are descriptive assessments based on observation, where as the SRP is a measure of self-perception and emotion and is complete by the child. Analyses will focus on individual subscales of the TRS and TRS composite scores, as Allen and colleagues (2010) indicated this scale, more so than the PRS and SRP, to be the most sensitive to TBI severity. Subtest data was available for between 107 participants.

The *Test of Memory and Learning* and *Test of Memory and Learning, Second Edition* (TOMAL and TOMAL-2; Reynolds & Bigler, 1994; Reynolds & Voress, 2007). The TOMAL and TOMAL-2 are tests of verbal and nonverbal memory, immediate and delayed recall, and attention/concentration. The TOMAL was developed for children and adolescents between the ages of 5 and 19 years, and is composed of 14 subtests, 10 that are core and four that are supplemental. The TOMAL was recently updated to the TOMAL-2 and is now suitable for individuals between 5-0 and 59-11 years of age. The TOMAL-2 is composed of eight core subtests, which aggregate to form a Verbal (Memory for Stories, Word Selective Reminding, Object Recall, and Paired Recall) and Nonverbal (Facial Memory, Abstract Visual Memory, Visual Sequential Memory, and Memory for Location), which can be combine to derive a Composite Memory Index. Additionally, there are six Supplementary Indexes (Verbal Delayed Recall Index, Attention/Concentration Index, Sequential Recall Index, Free Recall Index, Associative Recall Index, and Learning Index). Supplemental subtests are also divided into Verbal (Digits Forward, Letters Forward, Digits Backward, Letters Backward), and Nonverbal (Visual Selective Reminding and Manual Imitation). The TOMAL-2 subtests are scaled

to a mean of 10 and a standard deviation of 3 (range 1-20). Composite or summary scores are scaled to a mean of 100 and a standard deviation of 15 (Reynolds & Voress, 2007). The TOMAL and TOMAL-2 will be considered in this study as the TOMAL has displayed sensitivity to TBI on all indices and subtests, such that performance on the TOMAL helps to distinguish memory profiles and injury severity (Allen et al., 2010; Lowther & Mayfield, 2004) and only minimal changes were made between the two memory and learning batteries. Index scores were available for 121 participants.

Grooved Peg Board Test (GPBT; Tiffin, 1948*).* The GPBT is a widely used measure of motor speed and dexterity that requires subjects to fit keyhole-shaped pegs into similarly shaped holes. Scores included in the analyses were the time taken to place all of the pegs with the dominant and nondominant hands. Data for 97 of the participants was available.

Conners' Continuous Performance Test II (CPT-II; Conners & MHS Staff, 2000*).* The Conners' Continuous Performance Test II (CPT-II; Conners & MHS Staff, 2000) is a computer-administered task comprised of a series of letters presented intermittently on the computer screen, with time intervals of varying lengths occurring between the letters. Participants are asked to either press the space bar or click the mouse when a letter appears that is not the letter "X." Data from the CPT-II was available for 94 participants.

The Oral and Written Language Scales (OWLS; Carrow-Woolfolk, 1996*).* The OWLS is an individually administered assessment of receptive and expressive language for ages 3 through 21 years. The OWLS is comprised of three co-normed scales, namely Listening Comprehension (LC), Oral Expression, and Written Expression. Performance

on the LC scale was used as a measure of receptive language. Data was available for 104 participants.

Data Analysis

Comparisons will be made between the TBI and HC groups on demographic variables to determine the success of group matching based on the case selection method. Next, a series of cluster analyses will be run on TBI and HC samples. The descriptive and exploratory nature of cluster analysis requires that the experimenters are well versed in the cluster analytic literature, as well as have a strong theoretical rationale before analyzing the data. Before the cluster analysis process begins, several factors must be addressed, such as choosing the objects, the attributes, the cluster methods, the resemblance coefficients, and the final number of clusters. While this topic will be addressed in more depth later, the present study will consider the objects of the study, the participants, the attributes will be the five trials of the CTMT, clustering method will be Ward's method, the resemblance coefficient will be Squared Euclidian Distance, and we will ascertain data on a three, four, and five-cluster solution.

Subsequently, between group comparisons will then be conducted using multivariate analysis of variance (MANOVA) for the individual trials (1-5) and the composite score of the CTMT to establish the sensitivity of the CTMT to TBI. If necessary, post hoc univariate analyses (ANOVA) will be conducted to examine specific subtest and composite scores differences between the groups if overall MANOVAs are deemed significant.

Cluster Analysis

Cluster analysis is a multivariate taxometric procedure used to allocate objects or characteristics sharing similar attribute. This psychometric procedure has been used in many disciplines including biology, geology, anthropology, and marketing. Cluster analysis uses hierarchical methods of classification to identify heterogeneous groups of interest. The present study will use human subject performance on a measure of executive subprocesses across the lifespan, and will reduce particular qualities of level of performance as a function of age, into smaller homogenous groups. By reducing qualities of performance across the lifespan into smaller homogeneous groups, it is hoped that distinct clusters evidence, which may parallel the curvilinear relationship seen over development, maturation, and age associated decline of the brain regions most associated with executive subprocesses said to make up the Comprehensive Trail Making Test.

To classify heterogeneous groups into homogeneous subset (or clusters) individual similarity and differences of a group are quantified. Cluster analysis uses proximity, or distance between cases based on traits of interest, to determine whether certain groups are similar or dissimilar to one another; in theory, common variables as determined by proximity are thought to represent core features or endophenotypes, which distinguish one group from the next. While cluster analysis has the ability to show differential patterns of dysfunction, such analysis also shows unforeseen homogenous elements may emerge.

The hierarchical technique of cluster analysis assesses characteristics of interest and classifies them into groups. Repeating the process after determining one cluster

eventually forms an inverted tree structures, known as a dendrograms (Everitt, 1980). Dendrograms are two-dimensional diagrams which depict the convergence or divergence of groups made at successive stages of analysis. The groups representing each branch, or cluster, have been partitioned from the main characteristic of interest due to homogenous properties.

Within the hierarchical technique, multiple Agglomerative Method exist. Agglomerative methods appoint a similarity or distance matrix between characteristics of interest. The final product is a dendrogram illustrating the partitioning of one large, supposed heterogeneous, group of multiple homogenous groups (Everitt, 1980). The agglomerative methods of analysis are complete when all members of the main group are accounted for in a group.

Various clustering methods for research exist. A review of the literature ascertains the complete linkage clustering method (CLINK) and Ward's minimum variance method as two popularly used psychometric methods of analysis. Essentially, the CLINK method determines the two most similar objects and groups them together. After multiple objects from two-point clusters, larger clusters begin to form based on the distance, or maximum spanning value, between the initial two-object clusters. On the other hand, Ward's method forms larger clusters based on the object merging which results in the smallest increase in variance. Variance between object group is determined by a sum of squares formula (Everitt, 1980).

Despite evidence for both CLINK and Ward's method, the present study will apply Ward's minimum variance method of hierarchical cluster analysis to determine

whether subgroups of executive function abilities exist in healthy children, as well as those who have sustained a traumatic brain injury. In a four-stage sequential validation study, examining the properties of derivation, replication, external validation, and cross-validation, in 23 different methods of cluster analysis, by using data from 750 alcohol abusers on a multiple socio-behavioral variables, Ward's method of cluster analysis demonstrated particular powerful in comparison to solutions yielded by other techniques (Morey, Blashfield, and Skinner, 1983).

Ward's Method of cluster analysis maintains that the potential for clustering error exists within each stage of analysis, which may ultimately lead to the loss of information. To mitigate these circumstances, we can employ Squared Euclidean Distance as our resemblance coefficient to ensure that our established values are truly similar across all analyses. Cluster analytic studies often use resemblance coefficient to validate similarity in level and pattern of performance across neuropsychological measures (i.e., Donders, 1996; Donders, 1998; Mottram & Donders, 2006; Donders, 2008; Seaton, Goldstein, & Allen, 2001). The Euclidean distance coefficient is a calculation between two objects based on specific attributes, using a form of the Pythagorean Theorem. For instance, when two attributes are being compared, the resulting coefficient represents the length of the hypotenuse between two points of a right triangle. Simply, smaller coefficients represent greater similarity between two objects. In total, Ward's method creates homogenous cluster by considering the total sum of squared deviations of every point from the mean of the cluster to which it belongs. At each step of the analysis, union of every point or group member is considered and the group members whose union results

in the lowest increase in the error sum of squares are combined, creating a robust dendogram (Everitt, 1980).

In the present study, the objects will be the participants and the selection of attributes will be performance on the five trials of the CTMT. Raw scores of each trail (1-5) will be used in these analyses. As stated in Chapter 2 and based on supporting literature, we will use the Squared Euclidean Distance as our only resemblance coefficient across all analyses. Also introduced in Chapter 2 was the method of determining specific cluster solutions. Manually inspecting dendograms and determining where the best cutoff exists will determine cluster solutions. To our knowledge, no other researchers have conducted a cluster analysis of the CTMT standardization sample to parse patterns of performance across the lifespan. Thus, to account for the exploratory nature of this design, we will conduct analyses of three, four, and five cluster solutions. To ensure maximum use of cluster interpretation, any other solutions that evidences via dendograms will be considered. See Table 1 for a breakdown of the different age groups, methods, and cluster solutions that will be examined in the present study.

Once a cluster solution is configured, we will assess its internal validity and stability. In this case, internal validity will be determined by graphing the clusters in discriminant function space. Likewise, stability will be determined by conducting a second-stage k-means interactive partitioning cluster analysis with raw score means specified as starting points for each cluster centroid. It must be noted that the k-means method is nonhierarchical in nature. In this technique, predetermined centroids or "seeds" are established as the center of a preordained number of clusters. Once the seed has been

confirmed, other objects are assigned to a cluster based on the distance they are from the seed. A stable cluster solution would exhibit similar cluster membership with both hierarchical and iterative methods.

After stability has been established, Cohen's Kappa will be used to establish the level of agreement between clusters. Lastly, Beale's F-statistic (1969) will help us to choose which cluster solution was the most parsimonious compared to other solutions. As a whole, by considering the discriminant function space for internal validity, Cohen's Kappa, and the k-mean method for stability, as well as Beale's F-statistic for parsimony, is expected to assist in identifying which clustering solution is most suitable for the various levels and patterns of performance we will be examining in the CTMT. Briefly, external validity of the choice cluster solution will be examined by comparing our final solution on variables not included in the cluster analysis, including gender, ethnicity, and geographic region.

Procedure

The TBI sample was selected from a consecutive series of injury cases referred for neuropsychological evaluation at a restorative care facility. All assessments were administered by either a board certified neuropsychologist or doctoral level graduate students under the supervision of the neuropsychologist.

CHAPTER 3

RESULTS

Examination of the Matching Process

Demographic and clinical information for the groups are presented in Table 1. As can be seen from the Table, there were no significant differences between the groups for age, sex and ethnicity, indicating that the matching procedure was successful. Performance of each of the groups on the CTMT trial and composite scores are presented in Table 2. CTMT performance differences between the HC and TBI groups were examined via a Mixed-Model ANOVA and an overall significant effect was found, $F(5, 240) = 27.7$, $p < .01$. $\eta_p^2 = .370$. Follow-up ANOVAs found significant differences for all five trial scores and the CTMT composite scores, with the HC group performing around the standardization sample mean and the TBI group performing approximately 1.5 standard deviations below the HC group on the CTMT standard scores (see Table 2).

Cluster Analysis of the Traumatic Brain Injury Group

Cluster analyses, specifying a three, four, and five-cluster solutions, were conducted using Ward's method on the TBI sample and then the HC sample. Tables 3, 4 and 5, present results for the three-, four- and five-cluster solutions for the TBI group, with performance profiles for each of the solutions provided in Figures 1, 2, and 3.

As seen in Figure 1, the three-cluster solution for the TBI group generated clusters that differed predominantly on level of performance with a Low (C1), Impaired (C2), and Average (C3) cluster. The three-cluster's Average cluster had t-scores at or near the mean (50) across the five trials, where as the Low cluster had t-scores nearly 1.5 standard

deviations below the mean, and the Impaired cluster had t-scores between 2.5 and 3.0 standard deviations below the mean.

The four-cluster solution (see Figure 2) split the low cluster solution into a Low cluster (C1) and a new Low-Average cluster (C4). Particularly, individuals making up the low-average cluster differed from those of the low cluster in that they performed markedly better on trail 2 of the CTMT. The four-cluster's Average cluster had t-scores at or near the mean (50) across the five CTMT trials, t-scores of the Low-Average cluster vacillated between 0.6 and 1.4 standard deviations below the mean, the Low cluster had t-scores averaging nearly 1.75 standard deviations below the mean, and the Impaired cluster had t-scores between 2.5 and 3.0 standard deviations below the mean.

The five-cluster solution (see Figure 3) split the Average cluster into an Average cluster (C3) and a new Above-Average (C5) cluster, with markedly better performance on all trails of the CTMT, with the exception of trail four. The five-cluster's Above-Average cluster had t-scores between 0.4 and 1.0 standard deviations above the mean, the Average cluster had t-scores at or near the mean, the Low-Average cluster had t-scores between 0.6 and 1.4 standard deviations below the mean, the Low cluster had t-scores averaging nearly 1.75 standard deviations below the mean, and the Impaired cluster had t-scores between 2.5 and 3.0 standard deviations below the mean.

Cluster stability of the solutions was initially examined by discriminant function analysis (DFA). DFA correctly classified 95.0% of cases in the three-cluster solution, 95.0% of the cases making up the four-cluster solution, and 93.4% of cases in the five-cluster solution. Depictions of the three-, four-, and five-cluster solution in discriminant

function space are presented in Figures 7, 8, and 9, respectively. Qualitative inspection indicates the cluster solution exhibit adequate separation with little overlap between individual cases. Information regarding case misclassification for the three-, four-, and five-cluster solution are presented in Tables 9, 10, and 11, respectively. As can be seen from the tables, proper cluster classification occurred at a rate of 88.9% or greater, 77.1% or greater, and 88.9% or greater, for the three-, four-, and five-cluster solutions, respectively.

Stability and reliability of cluster membership were then evaluated using K-means iterative partitioning clustering method. Centroids were specified as the means for each of the five CTMT trials derived from the Wards cluster analyses. Cross-tabulation procedures compared the new K-mean clusters with the initial Ward's clustering solution. In this instance, Cohen's Kappa was employed as the stability measure.

Kappa values for the three-, four-, and five-cluster solutions were .90, .82, and .88, respectively. Results from all solutions indicate good agreement (Landis & Koch, 1977). Given the high classification rates of the three solutions and the adequate stability of the three- and five-cluster solutions, it was not possible to determine a choice cluster; additional statistical procedures were utilized to determine if one cluster solution accounted for more variance than another. Beale's F indicated that the four-cluster solution did not account for more variance than the three-cluster solution ($p > 0.05$). However, the five-cluster solution did account for more variance than the four-cluster solution ($p < 0.05$), and the five-cluster solution accounted for more variance than the three-cluster solution ($p < 0.05$). The foregoing analyses suggest that the three- and five-

cluster solutions may appropriately characterize the TBI group. Thus, the measures of external validity were examined to determine the best cluster solution for the TBI sample.

Cluster Analysis of the Healthy Control Group

The HC group's three-cluster solution had clusters that primarily differed on level of performance, with Above-Average (C1), Low (C2), and Average (C3) clusters. The three-cluster's above-average cluster had t-scores roughly between 1.0 and 1.6 standard deviations above the mean (50) across the five CTMT trials, whereas the average cluster had t-scores at or near the mean, and the low cluster had t-scores roughly between 0.6 and 1.2 standard deviations below the mean.

The four-cluster solution split the Above-Average cluster into a new Advanced (C4) cluster. Performance differences between the Above-Average and Advanced clusters were typified by marked deviations on trial 1 and 5 of the CTMT. The four-cluster's Advanced cluster had t-scores between 2.0 and 2.5 standard deviations above the mean, the Above-Average cluster had t-scores between 0.5 and 1.3 standard deviations above the mean, the Average cluster had t-scores at or near the mean, and the Low cluster had t-scores between 0.6 and 1.2 standard deviations below the mean.

The five-cluster solution split the Above-Average cluster into an Above-Average (C1) cluster, which depicted a slight curvilinear relationship from trial 1 to 5 of the CTMT and a new Decreasing-Performance (C3) cluster with noticeably elevated score on Trial 1, followed by a decrease in performance with subsequent trials. The five-cluster's Advanced cluster had t-scores between 2.0 and 2.5 standard deviations above the mean, the curvilinear-like Above-Average cluster had t-scores between 0.5 and 1.3 standard

deviations above the mean, the Decreasing-Performance cluster had t-scores beginning at 2.2 standard deviations above the mean and leveled out on trial 4 and 5 with t-scores 0.4 standard deviations above the mean, the Average cluster had t-scores at or near the mean, and the low cluster had t-scores between 0.6 and 1.2 standard deviations below the mean.

Stability of the three-, four-, and five-cluster solutions was examined by DFA. DFA correctly classified 90.9% of cases in the three-cluster solution, 93.4% of the cases in the four-cluster solution, and 90.9% of cases in the five-cluster solution. Depictions of the three-, four-, and five-cluster solution in discriminant function space are presented in Figures 10, 11, and 12, respectively. Qualitative inspection indicates the cluster solution exhibit adequate separation with little overlap between individual cases. Information regarding case misclassification for the three-, four-, and five-cluster solution are presented in Tables 12, 13, and 14, respectively. As can be seen from the tables, proper cluster classification occurred at a rate of 86.7% or greater, 76.5% or greater, and 85% or greater, for the three-, four-, and five-cluster solutions, respectively.

Stability and reliability of cluster membership were then evaluated using K-means iterative partitioning clustering method. Centroids were specified as the means for each of the five CTMT trials derived from the Wards cluster analyses. Cross-tabulation compared the new K-mean clusters with the initial Ward's hierarchical solution. Cohen's Kappa was used as the stability measure.

Kappa values for the three-cluster solution was .86; for the four-cluster solution, it was .84, and for the five-cluster solution it was .86. Results from all solutions indicate good agreement (Landis & Koch, 1977). Given the moderately high classification rates of

the three solutions and their adequate stability additional statistical procedures were employed to determine the choice cluster solution representing the HC group. The Beale's F statistic indicated that the four-cluster solution did account for more variance than the three-cluster solution ($p < 0.05$). The five-cluster solution accounted for more variance than the three-cluster solution ($p < 0.05$), but the five-cluster solution did not account for more variance than the four-cluster solution ($p > 0.05$). The foregoing statistics suggest that the four-cluster solutions most appropriately characterize performance of the HC group on the CTMT.

Examination of External Validity Variables for the TBI Three- and Five-Cluster Solutions

Demographic and Clinical Differences among the TBI Clusters

Demographic and clinical descriptive statistics for the three- and five-cluster TBI solutions are presented in Tables 15 and 16, respectively. Concerning the three-cluster solution, chi-square analyses indicated no significant differences among the clusters due to gender, χ^2 (2) = 2.11, p = .348, ethnicity, χ^2 (4) = 7.10, p = .312, open or closed head injury, χ^2 (2) = 5.42, p = .067, handedness, χ^2 (2) = 2.79, p = .247, mechanism of injury, χ^2 (8) = 12.85, p = .538. One-way ANOVAs identified no significant differences among the clusters due to age at assessment, F (2, 116) = 1.24, p = .294 and no significant difference among the clusters based on injury severity, as measured by the Glasgow Coma Scale scores, F (2, 79) = 1.08, p < .342.

Regarding the five-cluster solution, chi-square analyses indicated no significant differences among the clusters due to gender, χ^2 (2) = 2.50, p = .644, ethnicity, χ^2 (4) = 17.21, p = .142, open or closed head injury, χ^2 (2) = 5.42, p = .247, handedness, χ^2 (2) =

5.70, p = .223, mechanism of injury, χ^2 (8) = 35.22, p = .164. One-way ANOVAs identified significant differences among the clusters regarding months since sustained head injury, F (4, 114) = 2.83, p < .05, however, no significant difference evidenced among the clusters regarding age at injury F (4, 97) = 1.05, p = .384 or injury severity, measured by the Glasgow Coma Scale scores, F (4, 79) = 2.09, p = .09.

IQ, Achievement, and Neuropsychological Difference

IQ comparisons for the three-cluster solution indicated that the Impaired (C2) cluster performed poorer than the Low (C1) and Average (C3) cluster, but that the Low and Average clusters did not differ significantly from each other. A Mixed Model ANOVA examined potential differences on the Wechsler subtests (i.e., verbal, perceptual reasoning, and processing speed abilities) and found significant effects for Cluster, F(2, 109) = 33.27, p < .001, η_p^2 = .379, and for Wechsler subtest, F(2, 108) = 48.46, p < .001, η_p^2 = .473. A significant interaction effect for Cluster x Wechsler subtests was found, F(4, 216) = 2.87, p = .024, η_p^2 = .050. Post hoc Tukey's B analysis (Table 18) found that mean performance for all three clusters differed significantly at the p = .05 level. An overall visual inspection of the intelligence subtests suggested processing speed abilities were most impaired in the TBI group, whereas verbal ability was most preserved. A Mixed-Model ANOVA table for the three-cluster solution may be found in Table 17 and graphical representation of the verbal, perceptual reasoning, and processing speed indices can be found in Figure 13.

IQ comparisons for the five-cluster solution indicated that the Low (C1) and Impaired (C2) and Low-Average (C4) cluster solutions performed comparably and

markedly poorer than the Average (C3) and Above-Average (C5) clusters. A mixed model ANOVA examined potential differences on the Wechsler subtests (i.e., verbal, perceptual reasoning, and processing speed) and found significant effects for Cluster, $F(4, 107) = 18.72$, $p < .001$, $\eta_p^2 = .412$, and for Wechsler Subtest, $F(2, 106) = 32.80$, $p < .001$, $\eta_p^2 = .382$. An interaction effect for Cluster x Wechsler subtests was found, $F(8, 212) = 2.22$, $p < .027$, $\eta_p^2 = .077$. Post hoc Tukey's B analysis (Table 20) indicated that mean performance by the Impaired differed significantly from all clusters at the p = .05 level, with the exception of the Low cluster. Similar to the three-cluster solution, processing speed abilities appeared to best separate brain injury severity, while verbal abilities appeared relatively preserved and thus only slightly separated groups based on their severity. A Mixed-Model ANOVA table for the five-cluster solution may be found in Table 19. Graphical representation of WAIS indices may be found in Figure 14.

For achievement data pertaining to the three-cluster solution, mixed-model ANOVA found that the Impaired cluster performed worse than the Low cluster, which in turn performed worse than the Average cluster, on both Broad Reading and Broad Math composites. A significant effect for Cluster, $F(2, 113) = 32.26$, $p < .001$, $\eta_p^2 = .363$, and for Composite, $F(1, 113) = 8.07$, $p = .005$, $\eta_p^2 = .067$ evidenced, but indicated no Cluster x Composite interaction effect, $F(2, 113) = .498$, $p = .012$. Post hoc Tukey's B analysis (Table 22) found that the means for all clusters differed significantly at the $p = .05$ level. Visual inspection of the statistics suggested reading and mathematical abilities were nearly comparable in their ability to distinguish differences in executive subprocessing performance. A Mixed-Model ANOVA table for the three-cluster solution may be found

in Table 21. Graphical representation of the Achievement indices may be found in Figure 15.

Examination of the five-cluster solution indicated a decreased level of performance, such that the Above-Average cluster performed best, which was followed by the Average cluster, which was followed by the Low-Average cluster, and so forth. A significant effect for Cluster, $F(4, 111) = 20.50$, $p < .001$, $\eta_p^2 = .425$ and for Composite, $F(1, 111) = 4.71$, $p < .05$, $\eta_p^2 = .041$ evidenced, but no Cluster x Composite interaction effect, $F(4, 111) = 1.25$, $p = .043$ was present. Post hoc Tukey's B analysis (Table 24) found that mean performance for the Impaired cluster and Above-Average cluster differed significantly from all clusters at the $p = .05$ level. Mean performance between the Low and Low-Average clusters did not differ significantly, nor did mean performance between the Low-Average and Average clusters. Notwithstanding, mean performance by the Low cluster differed significantly from the Average cluster at the $p = .05$ level. Visual inspection evidenced reading and mathematical abilities were nearly comparable in their ability to distinguish cluster membership. However reading ability appeared to differentiate the Above-Average group from the others, where as mathematical ability appeared to be slightly better in differentiating between performance by the Impaired cluster and others. A Mixed-Model ANOVA table for the five-cluster solution may be found in Table 23. Graphical representation of the Achievement indices may be found in Figure 16.

With regard to memory, the three-cluster solution demonstrated a decreasing level of performance on the TOMAL index scores, such that performance was greatest for the

Average group, which was followed by the Low group, which was then followed by the Impaired group. Mixed-model ANOVA on TOMAL indexes found a significantly effect for Cluster, $F(2, 112) = 27.742$, $p < .001$, $\eta_p^2 = .331$, for TOMAL Index, $F(2, 111) = 7.66$, $p = .001$, $\eta_p^2 = .121$, and a significant Cluster x TOMAL Index interaction effect, $F(4, 222) = 3.18$, $p < .05$, $\eta_p^2 = .054$. Post hoc Tukey's B analysis (Table 26) found that the means for all clusters differed significantly at the $p = .05$ level. Inspection of the clusters suggested the Verbal Memory Index (VMI) differentiated the three clusters best, while performance on the Attention/Concentration Index (ACI) represented the least, albeit still significant, amount of variability between the clusters. A Mixed-Model ANOVA table for the three-cluster solution may be found in Table 25. Graphical representation of the TOMAL indices may be found in Figure 17.

The five-cluster solution also demonstrated differing levels and patterns of performance on the TOMAL index scores. Mixed-model ANOVA on TOMAL indexes found a significantly effect for Cluster, $F(4, 110) = 15.91$, $p < .001$, $\eta_p^2 = .367$, for TOMAL indices, $F(2, 109) = 7.05$, $p = .001$, $\eta_p^2 = .115$, but no significant Cluster x TOMAL Index interaction effect, $F(8, 218) = 2.48$, $p = .084$. Post hoc Tukey's B analysis (Table 31) found no difference between mean performance between the Impaired and Low clusters, Low and Low-Average clusters, and Low-Average, Average, and Above-Average clusters. Despite this finding, the Impaired cluster differed significantly from the three top-performing clusters and the Low cluster differed significantly from the Average and Above-Average clusters; these differences were significant at the $p = .05$ level. Similar to the three-cluster solution, the Verbal Memory Index (VMI) appeared to

differentiate the five clusters best, while performance on the Attention/Concentration Index (ACI) resulted in atypical variation. Specifically, the Above-Average cluster's pattern of performance indicated a significant decrease in performed ACI, such that individuals in this group performed worse than those in the Average group and nearly comparable to those in the Low-Average. Further, the five-cluster solution appeared to be characterized by increasing delayed recall and attentional/concentration abilities in the Impaired and Low clusters, which was opposite that of the Low-Average, Average, and Above-Average clusters. A Mixed-Model ANOVA table for the five-cluster solution may be found in Table 30. Graphical representation of the TOMAL indices may be found in Figure 21.

With regard to attentional differences between the three-cluster solution, mixed model ANOVA found a significant effect for Cluster, $F(2, 90) = 5.78$, $p < .01$, $\eta_p^2 = .114$, for CPT Score, $F(3, 88) = 7.96$, $p < .001$, $\eta_p^2 = .213$, but found no significant Cluster x CPT Score interaction effect, $F(6, 176) = .81$, $p = .566$. Post hoc Tukey's B analysis (Table 27) found mean performances of the Impaired and Low clusters did not differ significantly, and the Low and Average clusters did not differ significantly. Nonetheless, mean performance differed significantly between the Impaired and Average clusters at the p = .05 level. Follow up inspection of attentional differences using one-way ANOVAs indicated that Hit Rate best differentiated the three clusters, particularly the Average cluster from the Low and Impaired clusters. A Mixed-Model ANOVA table for the three-cluster solution may be found in Table 25. Graphical representation of the CPT indices may be found in Figure 18.

Concerning the five-cluster solution and attentional abilities, mixed model ANOVA found a significant effect for Cluster, $F(4, 88) = 4.32$, $p < .01$, $\eta_p^2 = .164$, for CPT Score, $F(3, 86) = 4.53$, $p < .01$, $\eta_p^2 = .136$, but no significant Cluster x CPT Score interaction effect, $F(12, 227) = .58$. Post hoc Tukey's B analysis (Table 32) indicated that mean performance by the Impaired and Low clusters differed significantly from mean performance by the Above-Average cluster at the p = .05 level. Visual inspection of the clusters indicated that more severe clusters had greater attentional problems, with the exception of Average cluster, which has poorer performance than the Low-Average cluster on most variables. Hit Rate Standard Error appeared to best parse performance differences between clusters. A Mixed-Model ANOVA table for the three-cluster solution may be found in Table 25. Graphical representation of the CPT indices may be found in Figure 22.

Concerning the three-cluster solution, significant ANOVA differences were also found for the OWLS receptive language score, $F(2, 116) = 15.45$, $p < .001$. Post hoc Tukey's B analysis (Table 28) indicated that performance means for all clusters differed significantly at the $p = .05$ level. Specifically, the Impaired cluster performed significantly poorer than the Low cluster, which performed significantly worse than the Average clusters. Graphical representation of the OWLS may be found in Figure 19.

Regarding the five-cluster solution, significant ANOVA differences were found OWLS receptive language score, $F(4, 116) = 8.35$, $p < .001$. Notably, Post hoc Tukey's B analysis (Table 33) found that the Impaired cluster differed significantly from all other

clusters, with the exception of the Low cluster at the $p = .05$ level. Graphical representation of the OWLS may be found in Figure 23.

Regarding the three-cluster solution's motor speed and fine-motor ability, as measured by the Grooved Pegboard Dominant and Non-dominate Hand performance (in seconds), mixed model ANOVA found significant effects for Cluster, $F(2, 86) = 13.86$, $p < .001$, $\eta_p^2 = .244$, and fine motor abilities, $F(1, 86) = 22.25$, $p < .001$, $\eta_p^2 = .206$. A significant interaction effect, $F(2, 86) = 1.65$, $p < .197$, $\eta_p^2 = .037$, also evidenced from the analyses. Post hoc Tukey's B analysis (Table 29) found that mean performance for the Impaired cluster differed significantly from the Low and Average clusters at the p = .05 level, when mean performance between the latter two clusters did not differ significantly. In this case, as in most others, the Impaired cluster performed worse than the Low cluster, which performed worse than the Average cluster. The Non-dominant Hand performance score best differentiated the three-cluster solution, particularly the Impaired cluster from the Low and Average clusters. While it took longer to perform the task with the nondominate hand, individuals in the Low and Average cluster performed at comparable rates among dominant and nondominate hand performance. A Mixed-Model ANOVA table for the three-cluster solution may be found in Table 25. Graphical representation of Grooved Pegboard performance may be found in Figure 20.

Concerning the motor speed and find-motor ability of the five-cluster solution, mixed model ANOVA found significant effects for Cluster, $F(4, 84) = 7.13$, $p < .001$, $\eta_p^2 = .250$, fine motor abilities, $F(1, 84) = 16.02$, $p < .001$, $\eta_p^2 = .160$, and an interaction effect, $F(4, 84) = 1.23$, $p < .304$, $\eta_p^2 = .055$. Post hoc Tukey's B analysis (Table 34)

found indicated significant differences in mean performance only regarding the Impaired cluster, such that the impaired cluster differed significantly from the all other clusters at the p = .05 level. Similar to the three-cluster solution, the Non-dominant Hand performance score best differentiated the five-cluster solution, particularly the Impaired cluster from the other clusters. Interestingly, the Low cluster performed slightly better than the Low cluster on the Non-dominate portion of the task. A Mixed-Model ANOVA table for the five-cluster solution may be found in Table 25. Graphical representation of Grooved Pegboard performance may be found in Figure 24.

Behavioral Comparisons across BASC Parent Rating Scale scores

A series of five MANOVAs were conducted on the BASC Parent Rating Scale (PRS), for the three- and five-cluster solutions, where cluster membership served as the between-subjects variable of the three- and five-cluster solution and BASC scores were the dependent variable. Given the overlap, index level analysis and subtest analysis were conducted separately. Specifically, analyses consisted of one MANOVA of the four BASC Indices; 1) Externalizing Problems Index, 2) Internalizing Problems Index, 3) Behavioral Symptoms Index, and 4) Adaptive Skills. Additionally, all four indices comprise three subscales, 1) Hyperactivity, Attention problems, Conduct Problems, 2) Anxious, Depressive, Somatization behavior, 3) Atypical behavior, Withdrawal, Attention problems, and 4) Adaptability, Social Skills, Leadership skills. The BASC analyses were conducted based on their theoretical and clinical relevance to TBI. Post hoc univariate analyses were used to examine specific subtest and index score differences between clusters when overall MANOVAs were significant.

Specific to the three-cluster solution of the PRS, analyses were first conducted on the three subscales making up the Externalizing Problems Index, which included the Hyperactivity, Attention problems, and Conduct Problems. The three subscales were treated as dependent variables in the MANOVA. Results from the MANOVA indicate significant results pertaining to the subscales, $F(2, 115) = 50.59$, $p < .001$, $\eta_p^2 = .468$. A non-significant effect was present for clusters, $F(2, 116) = 2.34$, $p = .101$ and there was no significant interaction effect $F(4, 230) = 1.17$, $p = .323$. Post hoc Tukey's B analysis found no significant differences between clusters.

The Internalizing Problems Index was assessed by considering parent ratings of their child's Anxious, Depressive, and Somatization behavior. The three Internalizing behaviors mentioned were treated as dependent variables in the MANOVA. Results from the MANOVA indicated a significant effects for the subscales, $F(2, 115) = 14.84$, $p < .001$, $\eta_p^2 = .205$. However, no significant differences were apparent for clusters, $F(2, 116) = 1.38$, $p = .255$, and the interaction effect was not significant, $F(4, 230) = .185$, $p = .946$. Despite the finding, Post hoc Tukey's B found significant differences in Somatization behavior scores between the Impaired and Average clusters at the p = .05 level.

The Behavioral Symptoms Index consists of Atypical behavior, Withdrawal, and Attention problems subtests, these three subtests were treated as dependent variables in the MANOVA. Results from the MANOVA indicate significant results pertaining to the subtests, $F(2, 115) = 67.88$, $p < .001$, $\eta_p^2 = .541$, as well as concerning the cluster, $F(2, 116) = 3.56$, $p < .05$, $\eta_p^2 = .058$. There was no significant interaction effect, $F(4, 230) =$

.825, $p = .510$. Post hoc Tukey's B analysis indicated no significant differences between clusters.

Parent ratings of their child's Adaptive Skills were assessed by the Adaptability, Social Skills, and Leadership skills subtests. The three subtests were treated as dependent variables in the MANOVA. Results from this MANOVA indicated a significant effect for the subscales, $F(2, 115) = 5.54$, $p < .01$, $\eta_p^2 = .088$, as well as a significant interaction effect, $F(4, 230) = 3.94$, $p < .01$, $\eta_p^2 = .064$, but no significant effect pertaining to the clusters themselves, $F(2, 116) = 1.63$, $p = .200$. Post hoc Tukey's B analysis found no significant differences between clusters.

The final analysis pertaining to the PRS was a MANOVA of all aforementioned composites scores. The above-mentioned indices were regarded as dependent variables in this MANOVA. Results from this MANOVA indicated a significant effect pertaining to the composite scores themselves, $F(3, 114) = 43.96$, $p < .001$, $\eta_p^2 = .536$, as well as a significant interaction effect, $F(6, 228) = 2.48$, $p < .05$, $\eta_p^2 = .061$, but no significant effect based on cluster, $F(2, 116) = 1.73$, $p = .181$. Post hoc Tukey's B analysis found no significant differences between clusters. A Mixed-Model ANOVA table for the three-cluster solution may be found in Table 35. Graphical representation of the Parent Rating Scale may be found in Figure 25.

Separately, the five-cluster solution of the Parent Rating Scale (PRS), analyses were first conducted on the three subtests making up the Externalizing Problems Index. The three subtests were considered dependent variables in this analysis. Results from the MANOVA indicated significant subscale results, $F(2, 113) = 34.39$, $p < .001$, $\eta_p^2 = .378$.

No significant difference evidenced among the clusters, $F(4, 114) = 1.57$, $p = .188$ and there was not significant interaction effect, $F(8, 226) = 1.04$, $p = .405$. Post hoc Tukey's B analysis indicated no significant differences between clusters.

Subscales making up the Internalizing Problems Index were assessed next. The three subtests were treated as dependent variables in this analysis. Results from the MANOVA indicated significant subscale results, $F(2, 113) = 9.30$, $p < .001$, $\eta_p^2 = .141$ regarding the subscales. However, no significant differences evidenced when comparing the clusters, $F(4, 114) = 965$, $p = .430$ or potential interaction effect, $F(8, 226) = 1.25$, $p = .042$. Post hoc Tukey's B analysis found no significant differences between clusters.

Three subscales making up the Behavioral Symptoms Index were treated as dependent variables in the next MANOVA. Results from this procedure indicated significant results pertaining to the subtests, $F(2, 113) = 44.73$, $p < .001$, $\eta_p^2 = .442$, as well as concerning the cluster, $F(4, 114) = 3.68$, $p < .05$, $\eta_p^2 = .114$. There was no significant interaction effect, $F(8, 226) = .316$, $p = .040$. Post hoc Tukey's B analysis found no significant differences between clusters.

Subsequently, the three subtests pertain to Adaptive Skills were treated as dependent variables and were assessed using a MANOVA. Results from this MANOVA indicated no significant effect for the subscales, $F(2, 113) = 1.87$, $p = .159$ or cluster, $F(4, 114) = 1.09$, $p < .365$, but found a significant interaction effect, $F(8, 226) = 3.348$, $p < .01$. Post hoc Tukey's B analysis found no significant differences between clusters.

The final analysis pertaining to the PRS was a MANOVA of all composites scores. The PRS indices were considered dependent variables in this analysis. Results

from this MANOVA indicated a significant effect pertaining to the composite scores, $F(3, 112) = 28.76$, $p < .001$, $\eta_p^2 = .435$, but no significant effect based on cluster, $F(4, 114) = 1.30$, $p = .275$. A significant interaction effect also evidenced, $F(12, 296) = 2.15$, $p < .05$, $\eta_p^2 = .071$. Post hoc Tukey's B analysis found no significant differences between clusters. A Mixed-Model ANOVA table for the five-cluster solution may be found in Table 36. Graphical representation of the Parent Rating Scale may be found in Figure 26.

CHAPTER 4

DISCUSSION

The current study provides useful information regarding higher-order cognitive functioning in children with TBI. Regarding the heterogeneous presentation of TBI, results support those found by others (e.g., Allen et al., 2010) and underscore the notion that no one profile of neurocognitive functioning appropriately characterizes children who have sustained a brain injury. Notwithstanding, the derived subgroups within the current sample may be distinguished by performance profiles on neuropsychological tests assessing executive subprocessing abilities.

Evidence supporting the validity of these subgroups was provided by an extensive comparison of the clusters on clinical, neuropsychological, and behavioral variables, as well as comparisons with clusters identified in an age- and gender-matched HC sample. Direct comparisons of the optimal TBI and HC cluster solutions addressed the proposal made by Crosson and colleagues (1990) regarding the importance of determining if variability in performance among TBI subgroups differed from what is expected variation in the normal population. To this end, variation outside that which is considered normal may be attributable to brain injury.

Specifically, it was hypothesized that at least three clusters would characterize the TBI group and that these clusters would differ by level of performance on the CTMT. Regarding the age- and gender-match HC group, we expected to identify at least three-clusters which would also differ predominantly on level of performance. While not necessarily hypothesized, it was expected that performance by the TBI group would be

characterized by more variability among CTMT trials than performance by the HC group. A second goal of this study was to assess the external validity of the optimal TBI cluster solution. To accomplish this, we examined whether the clusters identified in the TBI group differed from each other on important clinical variables, neuropsychological, and behavioral variables that were not included in the cluster analysis, and thus would provide external support for the validity of the optimal cluster solution. It was expected that these variables would provide additional support for the primary hypothesis regarding childhood TBI subtypes. Both hypotheses were thoroughly examined in this study and will, herein, be discussed.

Hypothesis I: Optimal Cluster Solutions for the TBI and Normal Control Groups

Statistical analyses conducted on the TBI sample indicated that the three-cluster solution was optimal for several reasons. First, DFA results suggest classification rate equal to or better than the other two cluster solutions (95%, versus 95% and 93.4%). Second, the solution had a higher level of agreement, as measured by Cohen's Kappa, than the other two solutions (.90 versus .82 and .88). Third, the solution exhibited adequate (albeit not necessarily the best), parsimony, as measured by Beale's F-statistic. Fourth, the optimal solution displayed the least amount of variability among the clusters, compared to the other two TBI cluster solutions. Lastly, the three-cluster solution appeared to generalize the best to clinical, neuropsychological, and behavioral measures of external validity. The latter-most point is associated with the second hypothesis and will be addressed in the section pertaining to external validity.

Examination of the CTMT cluster profiles for the three-cluster solution indicated that clusters differed predominantly in level of performance. These three clusters were labeled "Impaired", "Low", and "Average". As can be seen in Table 3 and Figure 1, performances across the five trials of the CTMT were relatively consistent. Interestingly, the final and presumed most difficult trail of the CTMT evidenced the highest standard scores for the Low and Impaired cluster, indicated those groups performed best on trial five. Conversely, the Average cluster performed worse on trial five, but had the highest standard score on trial four of the CTMT. Taken as a whole, these finding may indicate differences in learning or verbal comprehension, which warrant further investigation. Other studies utilizing cluster analysis have shown significant differences between Average performing clusters and other lower performing clusters on the verbal comprehension and memory abilities on the WISC-III and TOMAL, respectively (Allen et al., 2010; Thaler et al., 2010). Results from the current study support past findings and are addressed in the coming paragraph regarding measures of external validity.

Regarding specific clusters of the three-cluster TBI solution, the Average cluster obtained *T* scores for the CTMT trials between 48.7 and 52.4. Average cognitive performance across multiple domains has been noted by researchers who also utilize cluster analytic procedures as a means to identify homogeneous subgroups in seemingly heterogeneous samples of childhood TBI (see Allen et al., 2010; Donders & Warschausky, 1997; Thaler et al., 2010). For instance, Donders and Warschausky (1997) conducted a cluster analysis on WISC-III factor index scores using 153 children with TBI and found that children with TBI are capable of performing at what would be considered

"normal" levels for children in the general population. In a more recent cluster analytic study, Allen and colleagues (2010) assessed the memory and attention abilities in 150 children with TBI and 150 age- and gender-matched HC using the Test of Memory and Learning (TOMAL). Results from their analysis indicated that one of the clusters performed in the Average range on the TOMAL, as well as on most other intellectual, achievement, and neurocognitive measures (Allen et al., 2010). In another cluster analytic study, Thaler and colleagues (2010) examined IQ and behavioral profiles in 123 children with TBI. Results from their analysis indicated the presence of an Average cluster, which represented average performance on all WISC-III indexes, a similar finding to Donder and Warschausky (1997). Taken together, while children with TBI are capable of "normal" performance on various measures of cognitive functioning, researchers advise against referring to the group as such, given the likelihood of reduced neurocognitive abilities resulting from brain injury (Allen et al., 2010; Donders and Warschausky, 1997). In support of identifying Average performance, rather than "normal" performance, Donders and Warschausky (1997) found that the WISC-III performance was associated with socioeconomic status (SES), such that children comprising the below-average group came from lower SES backgrounds, whereas the opposite was true for the cluster characterized by high levels of performance. Other studies clarify this logic. For example, similar observations have been made in patients diagnosed with schizophrenia, who exhibit average performance across cognitive domains (Allen, Goldstein, & Warnick, 2003; Palmer et al., 1997) and also in patients with less neuroanatomical abnormalities and better outcomes (Allen et al., 2000; Wexler et al., 2009). Despite not knowing the

level of parental SES in the current study, this association provides rational for referring to the Average performance cluster as, Normal. Continuing, the Low cluster obtained mean *T* scores for the CTMT trail ranging from 33.4 to 37.7. The Low cluster consistently performed lower than the Average cluster on IQ, achievement, and neuropsychological variables and higher than the Impaired cluster, which obtained mean *T* scores for the CTMT trails ranging between 20.4 and 25.6.

Three-, four-, and five-cluster CTMT solutions were also derived for the HC group. As with the TBI group, all clusters were graphed in discriminant function space and underwent and a second-stage k-means interactive partitioning cluster analysis. Cohen's Kappa was used to establish the level of agreement between clusters. Lastly, Beale's F-statistic (1969) was utilized to identify which solution displayed the most parsimony. Based on these analyses, a four-cluster solution was identified as optimal for the HC group. The four-cluster solution was optimal for two main reasons. First, DFA results suggest classification rate equal to or greater than the other two cluster solutions (93.4%, versus 90.9% and 90.9%). Second, the solution had comparable levels of agreement, as measured by Cohen's Kappa, than the other two solutions (.84 versus .86 and .84). More specific comparisons between the optimal TBI and HC cluster solutions follow.

Separately and in general, the four-cluster HC solution differed on level of performance and was characterized by Low, Average, Above-Average, and Advanced performance on the CTMT. Interestingly, during trail five performances diverged. Insofar as, standard scores increased for the Advanced, Average, and to a lesser degree, the Low

cluster, and significantly decreased in the Above-Average cluster. This finding is unique and may suggest differential patterns of executive processing with increased cognitive demand. Also of note, while not necessarily hypothesized, it was expected that performance on the CTMT trials by the HC group would vary less than the TBI group. Contrary to this conjecture, results indicated that performance among trials of the CTMT varied less in the optimal cluster solution of the TBI group than in the optimal cluster solution of the HC group. Given that the CTMT trials progressively become more difficult by demanding more executive subprocesses, perhaps the data indicate varied learning patterns in healthy controls or possibly that the three-cluster TBI solution was more accurately categorized.

In comparing the TBI and HC groups, it was apparent that there was no statistically significant differences between them with respect to key demographic variables, suggesting not only that the matching procedure was successful, but that findings from this study may generalize to both boys and girls of different ages and ethnicity whose executive subprocessing abilities are assessed using the CTMT. Equally important was the finding that within the three-cluster solution, no significant differences evidenced with respect to gender, ethnicity, handedness, type and mechanism of head injury, age at assessment, or Glasgow Coma Scale score. This finding is thought to further support the use of cluster analysis as a statistical procedure to understand homogeneous subtypes in a seemingly heterogeneous sample. Understanding specific trial performance in the TBI group and then in the HC may help the reader understand

our concluding remarks regarding CTMT performance differences between the TBI and HC groups.

Based on the brief discussion regarding differences within the TBI and HC group, it is apparent that performance differences exist between healthy children and those who have sustained a traumatic brain injury. Highlighting these differences, the current study found the best performance within the three-cluster TBI solution to be average, whereas three of the four clusters in the four-cluster HC solution performed in that range or better. Given there were no statistically significant differences between the TBI and HC groups, with respect to demographic variables, it is presumed that performance by the TBI group was not simply the result of normal variability, but that sustaining a brain injury impaired higher-order cognitive functioning. The current findings support the notion that differential patterns of executive processing may evidence with increased cognitive demand. The TBI and HC cluster differences are consonant with those examining performance differences between TBI and HC on a number of neuropsychological measures, for example, the Test of Memory and Learning (e.g., compare Allen et al., 2010), as well as the Wechsler Intelligence Scales (e.g., compare Donders & Warschausky, 1997; Donders, 1996; and Thaler et al., 2010). The number of clusters and performance subtypes differed across the previously mentioned studies, which, according to Malec and colleagues (1993), is a function of the different measures utilized during the cluster analytic procedure. Despite this notion, however, there are consistencies across studies of children with TBI, which lends credence to the use of several neuropsychological tests in classifying brain injury subtypes. Next, differences of the TBI

group are addressed to support the decision of regarding the three-cluster TBI solution as optimal. A discussion of performance across assessment measures follows.

Hypothesis II: External Validity of the TBI Cluster Solution

Results of the analyses generally supported Hypothesis II, which predicted that examination of important external variables would support the three-cluster solution identified in the TBI group. Regarding measures of external validity, there were many statistically significant differences among the three-cluster TBI and level of performance. Despite the fact, the five-cluster solution was also assessed.

The three-cluster TBI solution clearly demonstrated level of performance differences on measures of intellectual ability. The Impaired cluster obtained the lowest scores on all three indices of the Wechsler scales. Such performance was followed by the Low cluster performing better than the Impaired cluster, and the highest scores on all four indices were obtained by the Average cluster. While the three-clusters differed in level of performance, they all exhibited the same intellectual strengths and weaknesses. Specifically, the most apparent weaknesses were on the processing speed index. Such deficits have been routinely found in cases of TBI (Axelrod et al., 2001) and may indicate a strong association between executive subprocessing deficits and processing speed impairments following brain injury. The low amount of variability in the verbal index may also suggest that verbal abilities are more preserved that other abilities measured by Wechsler subtests, following brain injury. In contrast, the five-cluster solution represented variable performance by the Average cluster, insofar as, the Average cluster scored slightly better than even the Above-Average cluster on the verbal index.

Notwithstanding, the Impaired and Low clusters maintained the poorest performance across the indices. Results concerning the intellectual functioning of children in the five-cluster solution do not accurately represent the differing levels of performance on the CTMT. Thus, In terms of intellectual functioning, it is believed the data present a clearer picture of differing levels of performance when considering the three-cluster TBI group as the optimal cluster solution.

The three-cluster TBI solution clearly demonstrated level of performance differences on measures of academic achievement. Achievement test performance in the areas of math and reading was similar to that observed with the IQ variables, in that, for the three-cluster solution, the Impaired cluster performed significantly worse than the Low cluster, and the Low cluster performed markedly poorer than the Average cluster, on both math and reading achievement. Results were similar for the five-cluster solution, such that scores on reading and math resulted a hierarchical performance, as the Above-Average cluster performed best, which was followed by the Average cluster, then the Low-Average cluster, and so forth. The Impaired cluster scored significantly lower than the other clusters on both reading and math ability, and the other clusters did not differ from each other. Both the three- and five-cluster solution had performance similar to the CTMT in terms of clear levels of performance. Thus, the Woodcock-Johnson scores on broad reading and broad math ability do not necessarily lend support to selecting one cluster solution over the other. While this may be the case, the similarity between the CTMT and academic achievement are noteworthy. Such findings suggest strong association between impairments in executive subprocessing and academic performance

following TBI in children and further suggest that membership in the most severely impaired subgroup could be useful for prediction educational outcomes and developing educational programming.

Memory deficits are common sequelae following brain injury (Allen et al., 2010; Babikian & Asarnow, 2009). Memory deficits in the three-cluster TBI solution were evident on all indices of the TOMAL and demonstrated clear levels of performance. Specifically, the VMI represented the greatest sensitivity to deficits in executive subprocessing, whereas the ACI differentiated clusters the least. In contrast, differences in the five-cluster solution were less clear. The Impaired, Low, and Low-Average cluster scored according to their classification, while performance by the Average and Above-Average group differed on the ACI. Similar to the three-cluster solution, the VMI was the most sensitive in terms of parsing levels of executive function performance and the ACI differentiated clusters the least. Such results may indicate that poorer memory results from poorer organizational and retrieval strategies, which is why long term memory scores correspond to deficits in higher-order cognitive functioning. In Allen and colleagues (2010) recent cluster analytic study using the TOMAL, they found that both the VMI and NMI differentiated clusters, and in a related study, that performance on the NMI was associated with the Perceptual Reasoning Index on the WISC-IV (Allen et al., 2010). In the current study, the NMI also indicated clear levels of performance in the three-cluster solution and were not necessarily associated with the measures of Perceptual Reason scores form the Wechsler scales. Similar to the evaluation of other external variables, the three-cluster solutions best accounted for performance on the TOMAL, as

post hoc analysis indicated all clusters significantly differing from each other, whereas the five-cluster solution represented almost dichotomous performance, as the Low and Impaired clustered did not significantly differ from each other, but did so when compared to all other clusters.

The three-cluster TBI solution clearly demonstrated level of performance differences on measures of sustained attention, inhibition, and impulsivity. Specifically, the three-cluster solution was stratified, such that the Impaired cluster performed worse, than the Low cluster, which performed worse than the Average cluster. The clusters were differentiated best by measures of Hit Rate Standard Error. Performance relating to the five-cluster solution also suggested that the Hit Rate Standard Error best separated performance, however, in most instances, the Average cluster performed poorer than the Low-Average cluster. While performance across injury severity was more uniform than other neurocognitive measures, the three-cluster solution appeared to best exemplify measures of attentional processing as they compare to executive subprocessing deficits. The deficits displayed by the three-cluster solution most accurately reflect higher-order cognitive function deficits were selected to represent the optimal cluster solution.

The three-cluster TBI solution clearly demonstrated level of performance differences with regard to dominant and non-dominant hand motor speed and dexterity, as measured by the Grooved Peg Board task. Results indicated the Impaired cluster performed worse, the Low cluster performed better, and the Average performed best. All clusters in the three-cluster solution differed significantly from each other. Deficits in executive subprocessing were most sensitive to nondominate hand. Performances by the

five-cluster solution were slightly less clear. Specifically, results indicated a similar hierarchical level of performance as the three-cluster solution, with the exception of the Low-Average and Average clusters, wherein the Low-Average cluster performed better than the Average cluster during dominate hand performance, and the opposite was true when considering non-dominate hand performance. Furthermore, post hoc analysis indicated that the five-cluster solution only had significant differences between the Impaired cluster, when compared to all the other cluster. Taken together, executive subprocessing abilities are likely mediated by the frontal lobes. It is therefore reasoned that the CTMT serves as a measure of frontal lobe function, and that the derived CTMT clusters may serve as an index of frontal lobe integrity. Given that motor abilities are also mediated by the frontal lobe, albeit the posterior portion, an association between motor abilities and higher-order cognitive functions should be made, such that both the CTMT and Grooved Pegboard should be sensitive to cerebral impairment. Given that GPB performance maps nicely onto the originally derived CTMT cluster solution, the three-cluster solution was retained as the optimal cluster solution.

Regarding behavior, parents rated their children via the parent rating scale (PRS) of the BASC. Results suggested that the behavioral disturbances were not necessarily associated with deficits in higher-order cognitive function, but rather appear to characterize children who had sustained a brain injury. Regarding the three-cluster solution, the Average cluster did not always display the least severe behavioral disturbances; rather scores from the Average and Low cluster seemed to alternate in terms of lower behavioral disturbance ratings. Regarding the BASC subscales, several

elevations were present (e.g., Anxiety, Atypicality, and Attention Problems), but none differed significantly between clusters. Regarding the composite scores, results indicated elevations in Externalizing problems and Behavioral Symptoms. Again, these scores did not differ significantly between clusters. Elevations such as these are consistent with recent literature concerning children with TBI (Thaler et al., 2010).

While behavior appeared more difficult to assess in the context of executive subprocessing performance, it was determined the three-cluster solution was optimal, as the parent rating reflected elevations which were described in earlier cluster analytic studies wherein Thaler and colleagues (2010) indicated that parents endorsed greater problems of attention and hyperactivity, a finding which corroborates results from the current study. In a similar study investigating memory abilities in children with TBI, Allen and colleagues (2010) found that parents endorsed more attention and conduct problems, but not hyperactivity. Despite the conduct subscale not being elevated in the current study, attention, hyperactivity, and conduct problems do comprise the Externalizing Index of the BASC and so one may likely infer externalizing problems being somewhat characteristic of children who have sustain a TBI. Moreover, the significant behavioral disturbances associated with the Impaired cluster may be expected given deficits in frontal lobe functions, such as attentional abilities, aspects of social skill functioning, as well as emotional and behavioral moderation are associated with regions of the frontal lobe.

Conclusion

The three-cluster solution was ultimately selected to represent the TBI group for four reasons. First, the three-cluster solution represented the most parsimonious solution with the fewest clusters. Second, the three-cluster solution represented distinct performance differences, which were supported by consistently significance post hoc analysis. Third, the current definition of TBI (mild, moderate, severe), supports a three-cluster solution. Fourth, and specific to the three-cluster solution, the Impaired cluster performed worse than the Low cluster, and the Low cluster performed worse than the Average cluster. While the majority of cases in the current study sustained moderate to severe injuries based on the GCS, performance differences on the CTMT were robust. Such findings point to the possibility of multiple gradations of TBI, which quantifiably impair neurocognitive domains. These results also point to the CTMT as a valuable indicator of milder TBI subtypes. There were also significant differences between the CTMT clusters on external validity variables, which provided further support for the validity of the three-cluster solution. In contrast, four clusters were identified as optimal for the HC group. The differences between the TBI cluster solution and HC cluster solutions were not accounted for by key demographic variables. The present results suggest that TBI results in heterogeneous patterns of executive function, which can not easily be accounted for by expected variability in test performance which are commonly observed in normal populations.

Limitations and Future Directions

The current study has a number of limitations that include potential variations in statistical power in detecting executive subprocessing cluster differences due to a limited number of participants. Based on the clinical nature of the cases, children with mild TBI were not included in the sample. Including mild cases in the TBI sample may have evidenced a high-average cluster. According to Allen and colleagues (2010), incorporation of mild TBI cases in a cluster analytic study may evidence in a cluster of above average premorbid intellectual abilities. Lastly, Anderson and Catroppa (2005) articulated that brain injury severity and lesion site did impact performance on measures of higher-order cognitive functioning. Results from the current study did not consider specific lesion sight and data regarding TBI severity was only presented through GCS scores. While the GCS diagnostic instrument is widely used by medical professionals, more specific information (e.g., neuroimaging results) may provide support to statistical procedures attempting to classify injury severity based on neuropsychological presentation.

Future studies may utilize the CTMT to shed light on the predictive quality of neuropsychological function and long-term cognitive recovery. Additionally, an examination of the cluster relationship in relation to specific site of injury, severity of trauma measured by neuroimaging technology, and length of coma and rehabilitation would provide valuable information. Future research may also apply functional imaging modalities during CTMT performance to identify specific regions of the brain associated with the subprocesses required to complete the task. Correlational analyses with diffusion

tensor imaging may also lend insight into the integrity of white matter connections between the frontal lobes and associated regions important for executive subprocesses.

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APPENDIX A

TABLES

Table 1.
Demographic and clinical information.

Variables	HC (n = 121)	TBI (n = 121)	F	p
Age (yrs)	M = 14.38 (SD = 2.57)	M = 14.58 (SD = 2.72)	.383	.535
Gender (% male)	62.0	63.6	.280	.597
% Ethnicity				
Caucasian	66.9	62.0		
African American	15.7	11.6		
Hispanic/Latino	14.9	17.3		
Asian American	0.0	1.7		
Other	2.5	7.4		
% Closed Head Injury		90.9		
% Mechanism of Injury				
Motor Vehicle Accident		43.8		
Struck by Motor		13.2		
Gunshot		5.8		
Fall		9.1		
4-wheel Accident		9.9		
Bike Accident		0.8		
Skiing		0.8		
Other		4.1		
GCS		M = 5.99 (SD = 3.17)		

Note. GCS = *Glasgow Coma Scale Score (3-15).*

Table 2.

MANOVA; CTMT performance between HC and TBI groups.

CTMT	HC (n = 121)		TBI (n = 121)		F-value	*p-value*	η_p^2
	Mean	*SD*	Mean	*SD*			
Trial 1	52.54	14.47	36.21	13.44	82.63	<.001	.256
Trial 2	52.95	12.40	35.61	13.01	112.62	<.001	.319
Trial 3	52.72	12.42	36.22	12.31	107.62	<.001	.310
Trial 4	51.17	12.17	35.81	13.92	83.45	<.001	.258
Trial 5	52.64	11.55	37.67	11.05	106.05	<.001	.306
Comp	52.16	11.40	34.77	12.02	133.39	<.001	.357

Note. T1 = Trial 1 of the CTMT, T2 = Trial 2, T3 = Trial 3, T4 = Trial 4, T5 = Trial 5, Comp = Composite Index.

Table 3.

Three-cluster solution for the TBI group using Ward's Method.

CTMT	Impaired C2 (n=32)		Low C1 (n=54)		Average C3 (n=35)	
	Mean	*SD*	Mean	*SD*	Mean	*SD*
Trial 1	23.06	5.96	34.44	8.54	50.97	9.99
Trial 2	20.41	3.33	36.00	8.07	48.91	9.27
Trial 3	22.41	5.4	35.54	7.58	49.91	6.74
Trial 4	21.69	4.19	33.44	8.64	52.4	8.48
Trial 5	25.59	5.54	37.68	5.73	48.68	9.47

Note. T1 = Trial 1 of the CTMT, T2 = Trial 2, T3 = Trial 3, T4 = Trial 4, T5 = Trial 5.

Table 4.

Four-cluster solution for the TBI group using Ward's Method.

CTMT	Impaired C2 (n=32)		Low C1 (n=36)		Low-Average C4 (n=18)		Average C3 (n=35)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Trial 1	23.06	5.96	31.97	6.64	39.39	9.89	50.97	9.99
Trial 2	20.41	3.33	31.75	5.42	44.5	5.29	48.91	9.27
Trial 3	22.41	5.4	33.39	6.59	39.83	7.76	49.91	6.74
Trial 4	21.69	4.19	32.08	9.27	36.17	6.65	52.4	8.48
Trial 5	25.59	5.54	36.22	5.46	40.61	5.24	48.69	9.47

Note. T1 = Trial 1 of the CTMT, T2 = Trial 2, T3 = Trial 3, T4 = Trial 4, T5 = Trial 5.

Table 5.

Five-cluster solution for the TBI group using Ward's Method.

CTMT	Impaired C2 (n=32)		Low C1 (n=36)		Low-Average C4 (n=18)		Average C3 (n=28)		Above-Average C5 (n=7)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Trial 1	23.06	5.96	31.97	6.64	39.39	9.89	48.64	9.22	60.29	7.52
Trial 2	20.41	3.33	31.75	5.42	44.5	5.29	46.36	7.57	59.14	8.76
Trial 3	22.41	5.4	33.39	6.59	39.83	7.76	48.21	5.79	56.71	6.26
Trial 4	21.69	4.19	32.08	9.27	36.17	6.65	51.79	7.27	54.86	12.67
Trial 5	25.59	5.54	36.22	5.46	40.61	5.24	45.75	7.59	60.43	6.95

Note. T1 = Trial 1 of the CTMT, T2 = Trial 2, T3 = Trial 3, T4 = Trial 4, T5 = Trial 5.

Table 6.

Three-cluster solution for the HC group using Ward's Method.

CTMT	Above-Average C1 (n=45)		Low C2 (n=39)		Average C3 (n=37)	
	Mean	SD	Mean	SD	Mean	SD
Trial 1	66.24	10.66	38.64	7.73	50.51	6.90
Trial 2	64.24	9.17	41.41	5.88	51.38	8.17
Trial 3	63.87	9.30	41.62	7.54	50.86	7.51
Trial 4	62.16	9.19	41.64	7.73	47.86	8.16
Trial 5	60.00	12.59	44.13	7.71	52.65	6.49

Note. T1 = Trial 1 of the CTMT, T2 = Trial 2, T3 = Trial 3, T4 = Trial 4, T5 = Trial 5.

Table 7.
Four-cluster solution for the HC group using Ward's Method.

CTMT	Above-Average C1 (n=34)		Low C2 (n=39)		Average C3 (n=37)		Advanced C4 (n=11)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Trial 1	63.18	9.81	38.64	7.73	50.51	6.90	75.73	7.21
Trial 2	62.53	7.57	41.41	5.88	51.38	8.17	69.55	11.82
Trial 3	61.82	8.54	41.62	7.54	50.86	7.51	70.18	9.05
Trial 4	59.21	7.94	41.64	7.73	47.86	8.16	71.27	6.50
Trial 5	55.09	8.87	44.13	7.71	52.65	6.49	75.18	10.12

Note. T1 = Trial 1 of the CTMT, T2 = Trial 2, T3 = Trial 3, T4 = Trial 4, T5 = Trial 5.

Table 8.
Five-cluster solution for the HC group using Ward's Method.

CTMT	Above-Avg. C1 (n=20)		Low C2 (n=39)		Decrease Per. C3 (n=14)		Average C4 (n=37)		Advanced C5 (n=11)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Trial 1	56.70	6.19	38.64	7.73	72.43	5.61	50.51	6.90	75.73	7.21
Trial 2	61.50	7.26	41.41	5.88	64.00	8.04	51.38	8.17	69.55	11.82
Trial 3	63.15	6.58	41.62	7.54	59.93	10.74	50.86	7.51	70.18	9.05
Trial 4	62.70	7.17	41.64	7.73	54.21	6.28	47.86	8.16	71.27	6.50
Trial 5	55.80	10.07	44.13	7.71	54.07	7.04	52.65	6.49	75.18	10.12

Note. T1 = Trial 1 of the CTMT, T2 = Trial 2, T3 = Trial 3, T4 = Trial 4, T5 = Trial 5.

Table 9.

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

		K-means Iteration			
Ward's Method		C1	C2	C3	Total
C1	Count	48	5	1	54
	Agreement	88.9%	9.2%	1.9	100%
C2	Count	0	32	0	32
	Agreement	0%	100%	0%	100%
C3	Count	2	0	33	35
	Agreement	5.7%	0%	94.3%	100%

Note. Kappa = .90, n = 121, T = 13.91, $p < .001$.

Table 10.

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

		K-means Iteration				
Ward's Method		C1	C2	C3	C4	Total
C1	Count	33	0	0	3	36
	Agreement	91.7%	0%	0%	8.3%	100%
C2	Count	4	28	0	0	32
	Agreement	12.5%	87.5%	0%	0%	100%
C3	Count	0	0	27	8	35
	Agreement	0%	0%	77.1%	22.9%	100%
C4	Count	1	0	0	17	18
	Agreement	5.6%	0%	0%	94.4	100%

Note. Kappa = .82, n = 121, T = 15.74, $p < .001$.

Table 11.

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

		K-means Iteration					
Ward's Method		C1	C2	C3	C4	C5	Total
C1	Count	32	0	0	4	0	36
	Agreement	88.9%	0%	0%	11.1%	0%	100%
C2	Count	4	28	0	0	0	32
	Agreement	12.5%	87.5%	0%	0%	0%	100%
C3	Count	0	0	25	3	0	28
	Agreement	0%	0%	89.3%	10.7%	0%	100%
C4	Count	0	0	0	18	0	18
	Agreement	0%	0%	0%	100%	0%	100%
C5	Count	0	0	0	0	7	7
	Agreement	0%	0%	0%	0%	100%	100%

Note. Kappa = .88, n = 121, T = 18.08, $p < .001$.

Table 12.

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

		K-means Iteration			
Ward's Method		C1	C2	C3	Total
C1	Count	39	0	6	45
	Agreement	86.7%	0%	13.3%	100%
C2	Count	0	34	5	39
	Agreement	0%	87.2	12.8%	100%
C3	Count	0	0	37	37
	Agreement	0%	0%	100%	100%

Note. Kappa = .86, n = 121, T = 13.58, $p < .001$.

Table 13.

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

		K-means Iteration				
Ward's Method		C1	C2	C3	C4	Total
C1	Count	26	0	3	5	34
	Agreement	76.5%	0%	8.8%	14.7%	100%
C2	Count	0	34	5	0	39
	Agreement	0%	87.2%	12.8%	0%	100%
C3	Count	1	0	36	0	37
	Agreement	2.7%	0%	97.3	0%	100%
C4	Count	0	0	0	11	11
	Agreement	0%	0%	0%	100%	100%

Note. Kappa = .84, n = 121, T = 15.36, $p < .001$.

Table 14.

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

		K-means Iteration					
Ward's Method		C1	C2	C3	C4	C5	Total
C1	Count	17	0	1	0	2	20
	Agreement	85.0%	0%	5.0%	0%	10.0%	100%
C2	Count	0	34	0	5	0	39
	Agreement	0%	87.2	0%	12.8%	0%	100%
C3	Count	1	0	13	0	0	14
	Agreement	7.1%	0%	92.9	0%	0%	100%
C4	Count	2	0	1	34	0	37
	Agreement	5.4%	0%	2.7%	91.9%	0%	100%
C5	Count	0	0	1	0	10	11
	Agreement	0%	0%	9.1	0%	90.9%	100%

Note. Kappa = .86, n = 121, T = 17.51, $p < .001$.

Table 15.

Descriptive and clinical variables of the three-cluster, TBI group.

Variables	Clusters			
	Impaired (C2)	Low (C1)	Average (C3)	Total
Gender *(n)*				
Male	17	36	24	77
Female	15	18	11	44
Ethnicity *(n)*				
Caucasian	18	32	25	75
African American	5	8	1	14
Hispanic	4	9	8	21
Asian American	0	2	0	2
Other	5	3	1	9
Injury *(n)*				
Open	5	6	0	11
Closed	27	48	35	110

	Mean	*SD*	Mean	*SD*	Mean	*SD*
AIY	15.77	2.55	14.01	2.80	14.40	2.48
WSI	21.00	25.04	18.88	21.52	12.91	15.07
GCS	5.33	2.79	6.00	3.07	6.75	3.74

Note. AIY = Age in Years; MSI = Weeks Since Injury; GCS = Glasgow Coma Scal

Table 16.

Descriptive and clinical variables of the five-cluster, TBI group.

Variables	Clusters								Total	
	Impaired (C2)		Low (C1)		Low-Average (C4)		Average (C3)	Above-Average (C5)		
Gender *(n)*										
Male	17		23		13		19	5		77
Female	15		13		5		9	2		44
Ethnicity *(n)*										
Caucasian	18		21		11		21	4		75
African Am.	5		3		5		1	0		14
Hispanic	4		8		1		5	3		21
Asian Am.	0		2		0		0	0		2
Other	5		2		1		1	0		9
Injury *(n)*										
Open	5		4		2		0	0		11
Closed	27		32		16		28	7		110
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
AIY	15.77	2.55	13.91	3.03	14.23	2.34	14.36	2.64	14.57	1.90
MSI	21.00	25.05	12.39	11.77	28.89	31.09	11.33	12.01	20.00	25.08
GCS	5.33	2.79	5.09	2.25	7.62	3.71	7.00	3.88	5.75	3.40

Note. AIY = Age in Years; MSI = Months Since Injury; GCS = Glasgow Coma Scale.

Table 17.

Mixed-Model ANOVA; IQ Difference across the three-cluster solution, TBI group.

Variables	Clusters						*F*-value	*p*-value	η_p^2
	Impaired (C2) (n = 26)		Low (C1) (n = 53)		Average (C3) (n = 33)				
	Mean	*SD*	Mean	*SD*	Mean	*SD*			
Intelligence							33.27	<.001	0.379
VERB	86.07	15.73	88.92	15.88	97.63	14.17			
PR	81.57	14.19	91.26	11.44	103.51	9.07			
PS	67.11	10.33	80.15	9.98	91.88	8.50			

Note. VERB = Verbal; PR = Perceptual Reasoning; PS = Processing Speed.

Table 18.

Post hoc Tukey's B analysis, ***Intelligence, three-cluster solution, TBI group.***

		Subset		
Cluster	N	1	2	3
Impaired (C2)	26	78.26		
Low (C1)	53		86.78	
Average (C3)	33			97.68

Table 19.

Mixed-Model ANOVA; IQ Difference across the five-cluster solution, TBI group.

Variables	Clusters										*F*-value	*p*-value	η_p^2
	Impaired (C2) (n = 26)		Low (C1) (n = 35)		Low-Avg. (C4) (n = 18)		Average (C3) (n = 26)		Above-Avg. (C5) (n = 7)				
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*			
Intelligence											18.71	< .001	0.412
VERB	86.07	15.24	88.65	17.32	89.44	13.08	97.88	14.82	96.71	12.45			
PR	81.57	14.19	88.25	11.05	97.11	10.08	102.77	9.24	106.29	8.42			
PS	67.11	10.33	77.37	10.17	85.56	7.13	90.19	8.28	98.14	6.41			

Note. VERB = Verbal; PR = Perceptual Reasoning; WM = Working Memory; PS = Processing Speed.

Table 20.
Post hoc Tukey's B analysis, Intelligence, five-cluster solution, TBI group.

		Subset			
Cluster	N	1	2	3	4
Impaired (C2)	26	78.26			
Low (C1)	35	84.76	84.76		
Low-Average (C4)	18		90.70	90.70	
Average (C3)	26			96.95	96.95

Table 21.
Mixed-Model ANOVA; WJ-III-ACH, Achievement Difference across the three-cluster solution, TBI group.

Variables	Clusters						*F*-value	*p*-value	η_p^2
	Impaired (C2) (n = 31)		Low (C1) (n = 54)		Average (C3) (n = 35)				
	Mean	*SD*	Mean	*SD*	Mean	*SD*			
Achievement							22.56	<.001	0.278
BR	69.35	25.84	84.59	17.31	97.29	13.26			
BM	70.32	25.87	88.00	16.34	101.34	11.27			

Note. BR = Broad Reading abilities; BM = Broad Math abilities.

Table 22.
Post hoc Tukey's B analysis, Achievement, three-cluster solution, TBI group.

		Subset		
Cluster	N	1	2	3
Impaired (C2)	28	77.32		
Low (C1)	53		87.92	
Average (C3)	35			99.31

Table 23.
Mixed-Model ANOVA; Achievement Difference across the five-cluster solution, TBI group.

Variables	Clusters										*F*-value	*p*-value	η_p^2
	Impaired (C2) (n = 31)		Low (C1) (n = 36)		Low-Avg. (C4) (n = 18)		Average (C3) (n = 28)		Above-Avg. (C5) (n = 7)				
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*			
Achievement											12.98	<.001	0.311
BR	69.35	25.84	82.31	17.92	89.17	15.49	94.00	11.67	110.43	11.46			
BM	70.32	25.87	84.89	18.19	94.22	9.50	99.57	10.75	108.43	11.24			

Note. BR = Broad Reading abilities; BM = Broad Math abilities.

Table 24.
Post hoc Tukey's B analysis, Achievement, five-cluster solution, TBI group.

Subset

Cluster	N	1	2	3	4
Impaired (C2)	26	77.32			
Low (C1)	35		85.99		
Low-Average (C4)	18		91.69	91.69	
Average (C3)	26			96.79	
Above-Average (C5)	7				109.43

Table 25.

Mixed-Model ANOVA; Neuropsychological Difference across the three-cluster solution, TBI group.

Variables	Clusters	*F*-value	*p*-value	η_p^2

	Impaired (C2)		Low (C1)		Average (C3)				
	Mean	*SD*	Mean	*SD*	Mean	*SD*			
Memory							26.37	<.001	0.320
VMI	69.29	18.53	81.90	14.60	94.12	13.39			
NMI	70.87	18.80	88.53	17.77	99.45	9.57			
ACI	75.84	15.61	84.41	14.05	91.42	14.65			
Attention							5.78	<.005	0.114
CPTHR	62.06	16.01	54.54	12.27	50.03	11.97			
CPTSE	65.02	16.70	57.71	14.68	52.23	14.77			
CPTVAR	62.27	17.06	56.21	15.37	52.09	14.78			
CPTP	59.29	21.22	53.30	15.12	48.53	8.59			
Motor Speed							13.86	<.001	0.244
GPD Time	102.20	35.48	83.18	15.64	69.13	11.49			
GPN Time	130.87	56.62	96.39	37.49	80.23	23.34			

Note. VMI = Verbal Memory Index; NMI = Nonverbal Memory Index; ACI = Attention/Concentration Index; CPTHR = Continuous Performance Test-Hit Rate; CPTHRSE = Continuous Performance Test-Standard Error; CPTVAR = Continuous Performance Test-Variability of Standard Errors; CPTP = Continuous Performance Test-Perseverations; GPD Time = Grooved Pegboard-Dominant Hand Time (in seconds); GPD Error = Grooved Pegboard-Dominant Hand Error; GPN Time = Grooved Pegboard-Nondominant Hand Time (in seconds); GPN Error = Grooved Pegboard-Nondominant Hand Error.

Table 26.

Post hoc Tukey's B analysis, Memory, three-cluster solution, TBI group.

	Subset

Cluster	N	1	2	3
Impaired (C2)	31	72.00		
Low (C1)	51		84.95	
Average (C3)	33			95.00

Table 27.
Post hoc Tukey's B analysis, Attention, three-cluster solution, TBI group.

	Subset

Cluster	N	1	2
Average (C3)	27	50.72	
Low (C1)	44	55.44	55.44
Impaired (C2)	22		62.16

Table 28.
Post hoc Tukey's B analysis (ANOVA), OWLS Receptive Language, three-cluster solution, TBI group.

	Subset for alpha = 0.05

Cluster	N	1	2	3
Impaired (C2)	30.00	80.30		
Low (C1)	52.00		92.50	
Average (C3)	35.00			100.46

Table 29.
Post hoc Tukey's B analysis, Motor, three-cluster solution, TBI group.

	Subset

Cluster	N	1	2
Average (C3)	30	74.68	
Low (C1)	44	89.78	
Impaired (C2)	15		116.53

Table 30.

Mixed-Model ANOVA; Neuropsychological Difference across the five-cluster solution, TBI group.

Variables	Clusters										*F*-value	*p*-value	η_p^2
	Impaired (C2)		Low (C1)		Low-Avg. (C4)		Average (C3)		Above-Avg. (C5)				
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*			
Memory											15.91	<.001	0.367
VMI	69.29	18.53	77.56	14.28	90.59	11.21	92.41	13.92	101.83	7.28			
NMI	70.87	18.80	84.12	16.69	97.35	16.96	99.00	10.25	101.50	5.75			
ACI	75.84	15.61	82.88	12.55	87.47	16.65	92.19	15.94	88.00	5.93			
Attention											4.32	<.005	0.164
CPTHR	62.06	16.01	55.88	11.18	52.20	14.05	51.34	12.37	46.30	10.72			
CPTSE	65.02	16.70	60.88	13.87	52.16	14.82	54.22	15.31	46.56	12.36			
CPTVAR	62.27	17.06	59.44	15.04	50.56	14.71	53.99	15.42	46.69	12.17			
CPTP	59.29	21.22	56.10	17.92	48.41	6.09	49.26	9.89	46.44	1.80			
Motor Speed											7.13	<.001	0.254
GPD Time	102.20	35.48	83.63	15.14	82.47	16.85	70.48	10.98	64.71	12.88			
GPN Time	130.87	56.62	92.37	19.20	102.76	55.74	83.30	25.08	70.14	13.11			

Note. VMI = Verbal Memory Index; NMI = Nonverbal Memory Index; ACI = Attention/Concentration Index; CPTHR = Continuous Performance Test-Hit Rate; CPTHRSE = Continuous Performance Test-Standard Error; CPTVAR = Continuous Performance Test-Variability of Standard Errors; CPTP = Continuous Performance Test-Perseverations; GPD Time = Grooved Pegboard-Dominant Hand Time (in seconds); GPD Error = Grooved Pegboard-Dominant Hand Error; GPN Time = Grooved Pegboard-Nondominant Hand Time (in seconds); GPN Error = Grooved Pegboard-Nondominant Hand Error.

Table 31.

Post hoc Tukey's B analysis, Memory, five-cluster solution, TBI group.

	Subset

Cluster	N	1	2	3
Impaired (C2)	31	72.00		
Low (C1)	34	81.52	81.52	
Low-Average (C4)	17		91.80	91.80
Average (C3)	27			94.53
Above-Average (C5)	6			97.11

Table 32.
Post hoc Tukey's B analysis, Attention, five-cluster solution, TBI group.

	Subset		

Cluster	N	1	2
Above-Average (C5)	7	46.50	
Low-Average (C4)	16	50.83	50.83
Average (C3)	20	52.20	52.20
Low (C1)	28		58.08
Impaired (C2)	22		62.16

Table 33.
Post hoc Tukey's B analysis (ANOVA), OWLS Receptive Language, five-cluster solution, TBI group.

	Subset for alpha = 0.05

Cluster	N	1	2	3
Impaired (C2)	30	80.30		
Low (C1)	34	90.76	90.76	
Low -Average (C4)	18		95.78	95.78
Average (C3)	28		99.21	99.21
Above-Average (C5)	7			105.43

Table 34.
Post hoc Tukey's B analysis, Motor, five-cluster solution, TBI group.

	Subset

Cluster	N	1	2
Above-Average (C5)	7	67.43	
Average (C3)	23	76.89	
Low (C1)	27	88.00	
Low-Average (C4)	17	92.62	
Impaired (C2)	15		116.53

Table 35.
MANOVA; Behavior Assessment System for Children, PRS scores across the three-cluster solution, TBI group.

Variables	Clusters						*F*-value	*p*-value	η_p^2
	Impaired (C2) (n =29)		Low (C1) (n =48)		Average (C3) (n =31)				
	Mean	*SD*	Mean	*SD*	Mean	*SD*			
Externalizing Problems									
Hyperactivity	54.28	12.38	56.75	14.23	54.08	20.01	.145	.866	.007
Conduct problems	55.89	15.51	51.00	7.88	55.08	23.64	.419	.660	.019
Aggression problems	54.17	9.72	51.44	8.61	54.85	21.81	.259	.773	.012
Internalizing Problems									
Anxiety	55.14	12.27	50.00	11.74	49.03	13.82	2.12	.125	.039
Depression	59.34	15.78	56.10	13.36	53.65	14.74	1.17	.313	.022
Somatization	53.28	10.23	50.29	12.80	46.64	9.69	2.59	.080	.047
Behavioral Symptoms									
Atypicality	55.22	9.38	58.00	16.54	49.46	9.51	1.76	.184	.074
Withdrawal	52.11	11.45	53.06	15.52	46.77	8.02	1.07	.350	.047
Attention Problems	61.55	12.16	62.88	9.18	56.69	15.26	.996	.377	.043
Adaptive Skills									
Adaptability	49.00	14.72	48.75	4.72	56.25	10.14	.637	.551	.124
Social Skills	41.00	7.83	48.75	12.66	46.75	10.37	.590	.574	.116
Leadership	39.25	6.70	52.75	8.18	52.50	7.85	4.13	.054	.478
PRS Composite									
Externalizing	55.56	12.65	53.56	9.21	55.69	25.29	.084	.920	.004
Internalizing	52.72	7.21	51.69	12.08	46.54	9.96	1.62	.209	.069
Behavior symptoms	57.28	9.63	56.63	11.04	53.08	17.97	.442	.646	.020
Adaptive Skills	42.06	7.60	40.86	7.97	47.08	12.09	1.82	.175	.076

Note. PRS = Parent Rating Scale.

Table 36.

MANOVA; Behavior Assessment System for Children, PRS scores across the five-cluster solution, TBI group.

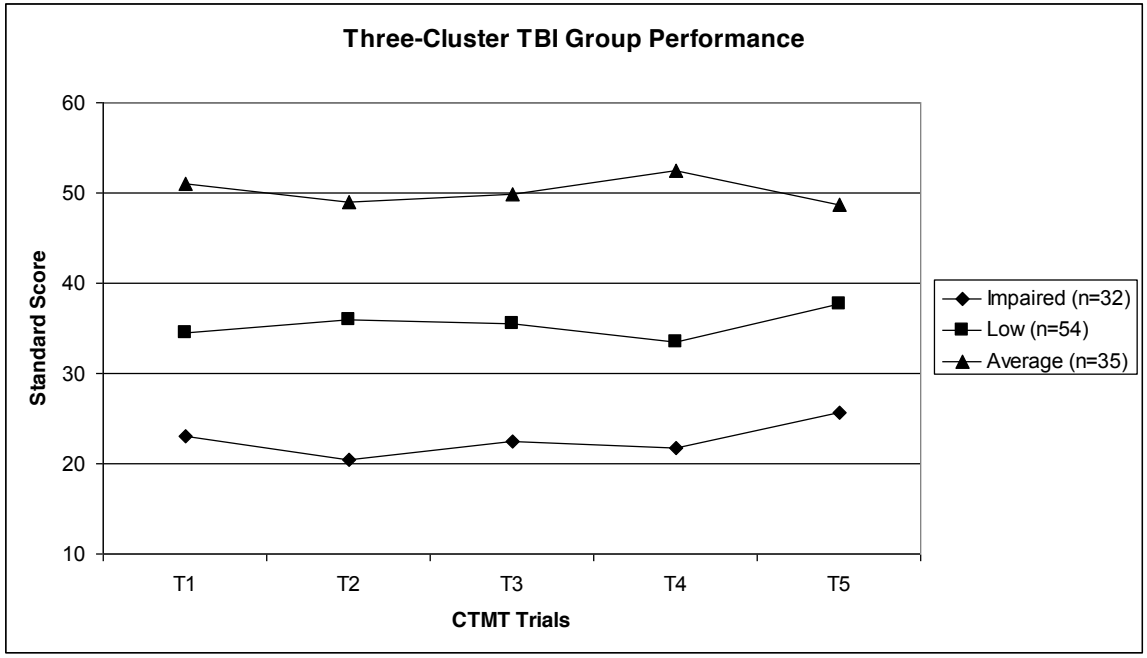
Variables	Clusters										*F*	*p*-value	η_p^2
	Impaired(C2) (n = 31)		Low (C1) (n = 36)		Low-Avg. (C4) (n = 17)		Average (C3) (n = 28)		Above-Avg.(C5) (n = 7)				
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*			
Externalizing Problems													
Hyperactivity	54.28	12.39	56.25	17.85	57.25	11.27	57.75	23.87	48.20	11.56	0.36	0.83	0.03
Conduct problems	55.89	15.51	49.38	8.33	52.63	7.60	60.50	29.13	46.40	6.31	0.83	0.51	0.07
Aggression problems	54.17	9.73	51.13	9.33	51.75	8.46	57.38	27.12	50.80	10.35	0.30	0.88	0.03
Internalizing Problems													
Anxiety	55.14	12.27	48.56	10.30	52.88	14.12	48.52	14.51	51.17	11.36	1.42	0.23	0.05
Depression	59.34	15.78	56.94	12.85	54.44	14.62	53.96	16.19	52.33	6.56	0.67	0.61	0.03
Somatization	53.28	10.23	49.66	11.83	51.56	14.90	45.28	9.04	52.33	11.09	1.84	0.13	0.07
Behavioral Symptoms													
Atypicality	55.22	9.38	57.88	21.34	58.13	11.42	52.00	11.10	45.40	4.72	1.07	0.38	0.09
Withdrawal	52.11	11.45	48.88	11.81	57.25	18.34	46.63	7.29	47.00	10.00	1.00	0.42	0.09
Attention Problems	61.56	12.16	57.38	6.80	68.38	8.07	58.50	18.21	53.80	10.03	1.48	0.22	0.12
PRSComposite													
Externalizing	55.56	12.65	52.63	11.69	54.50	6.59	60.38	31.10	48.20	10.57	0.48	0.75	0.04
Internalizing	52.72	7.22	49.63	10.41	53.75	13.95	44.75	10.85	49.40	8.65	1.14	0.35	0.10
Behavior Symptoms	57.28	9.63	54.25	12.57	59.00	9.52	55.50	21.91	49.20	9.88	0.53	0.71	0.05

Note. PRS = Parent Rating Scale.

APPENDIX B

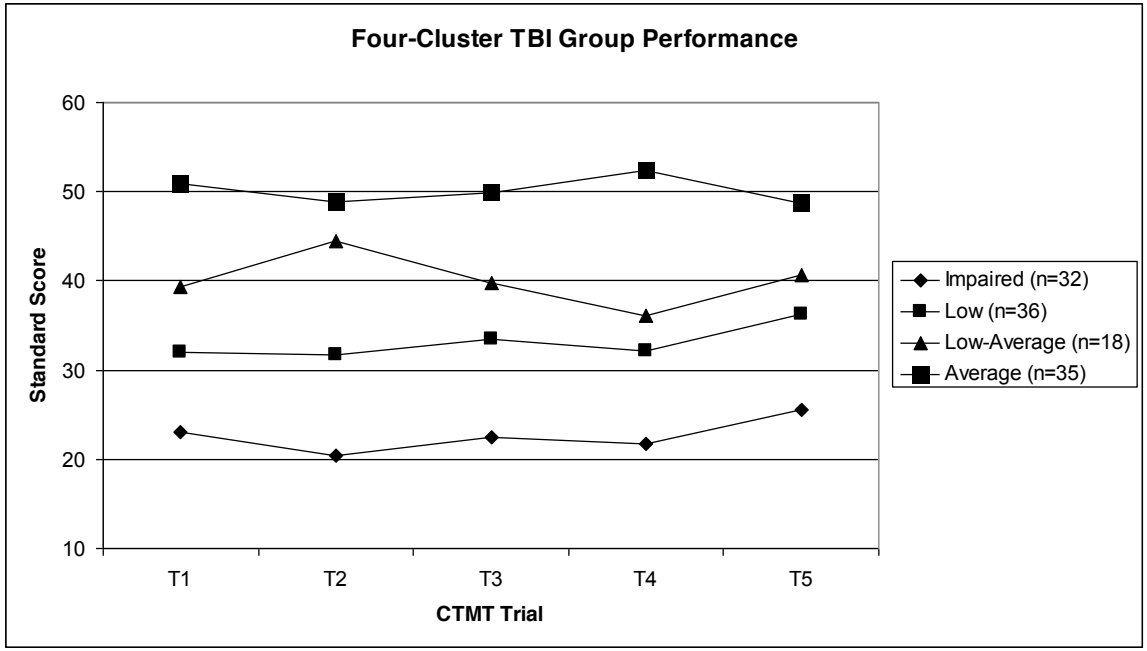
FIGURES

Figure 1.
Graphical Representation of Ward's Cluster Analysis ***Method: 3 Cluster, TBI group.***



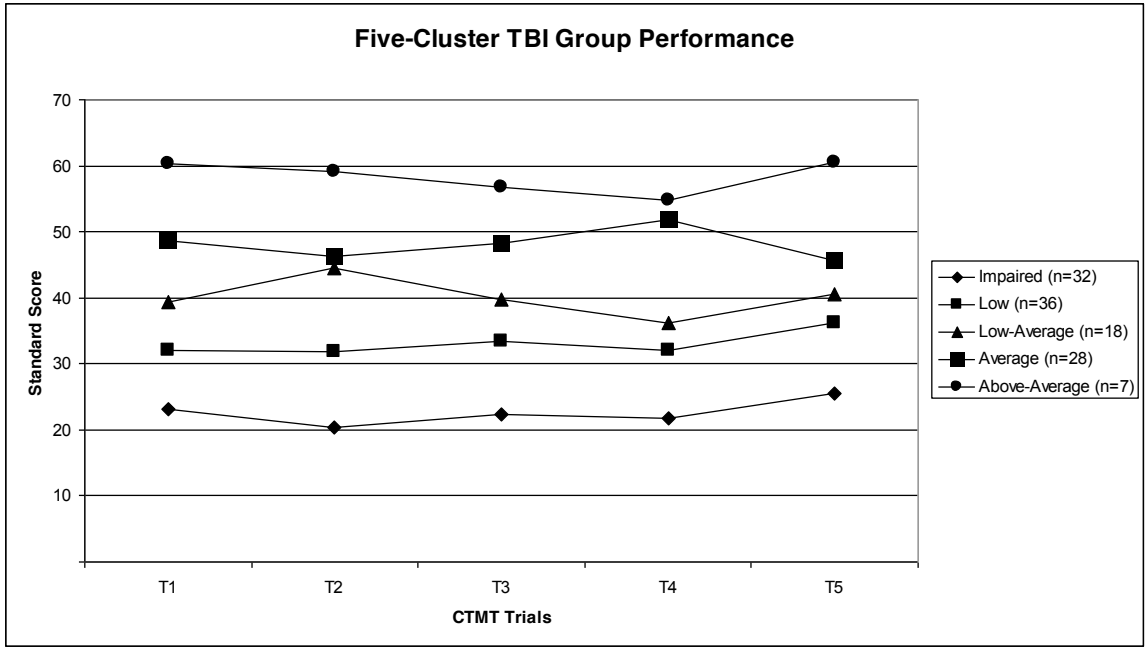
Note. T1 = Trial 1 of the CTMT, T2 = Trial 2, T3 = Trial 3, T4 = Trial 4, T5 = Trial 5, Standard Score (x bar = 50).

Figure 2.
Graphical Representation of Ward's Cluster Analysis ***Method: 4 Cluster, TBI group.***



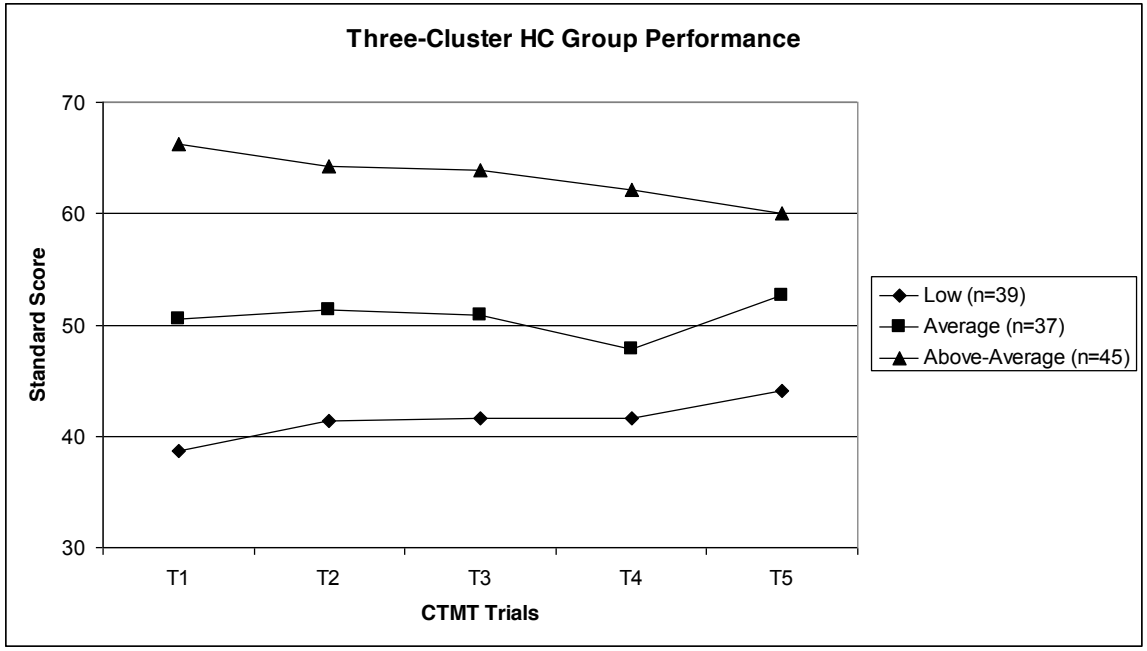
Note. Please see Figure 1 for explanation of abbreviations.

Figure 3.
Graphical Representation of Ward's Cluster Analysis Method: 5 Cluster, TBI group.



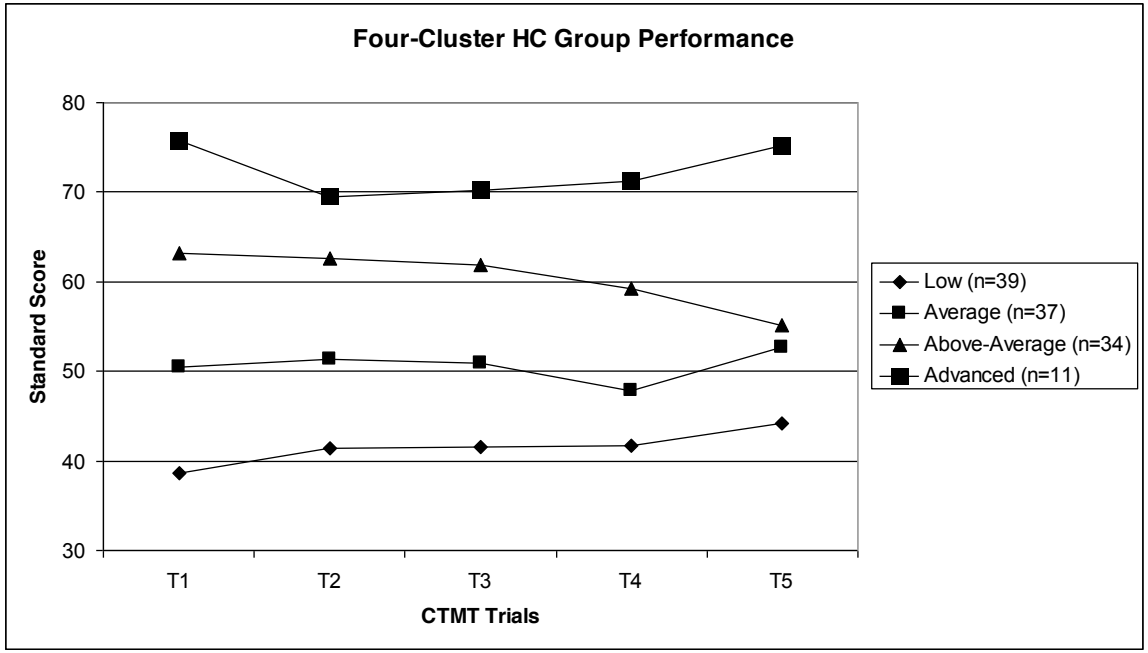
Note. Please see Figure 1 for explanation of abbreviations.

Figure 4.
Graphical Representation of Ward's Cluster Analysis Method: 3 Cluster, HC group.



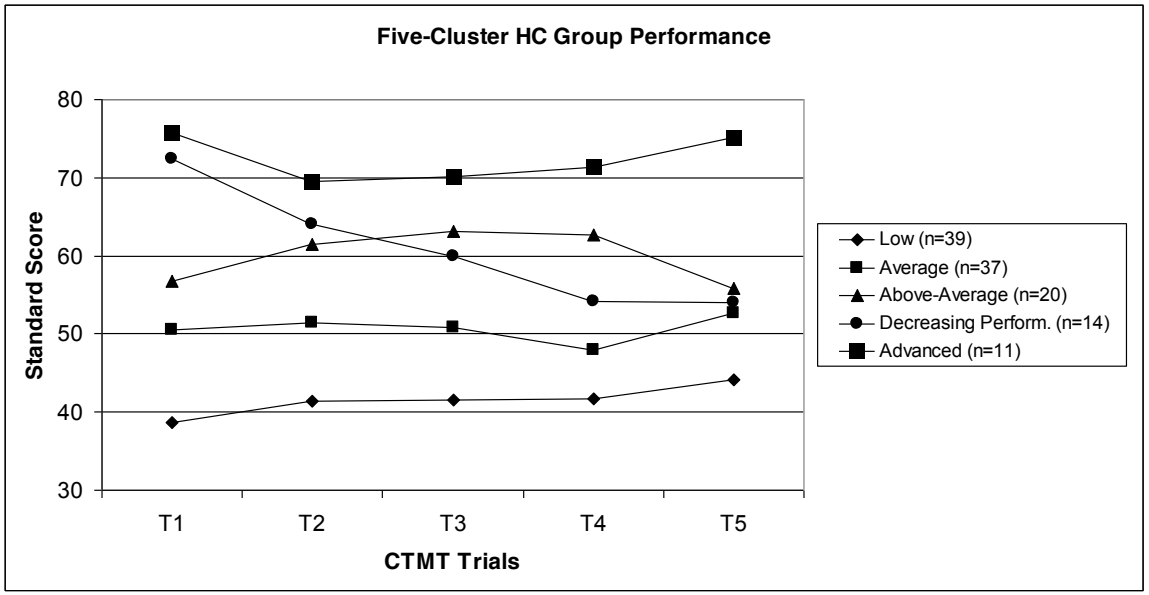
Note. Please see Figure 1 for explanation of abbreviations.

Figure 5.
Graphical Representation of Ward's Cluster Analysis Method: 4 Cluster, HC group.



Note. Please see Figure 1 for explanation of abbreviations.

Figure 6.
Graphical Representation of Ward's Cluster Analysis Method: 5 Cluster, HC group.



Note. Please see Figure 1 for explanation of abbreviations.

Figure 7.
Three-Cluster TBI solution, DFA of CTMT trials using Ward's Method.

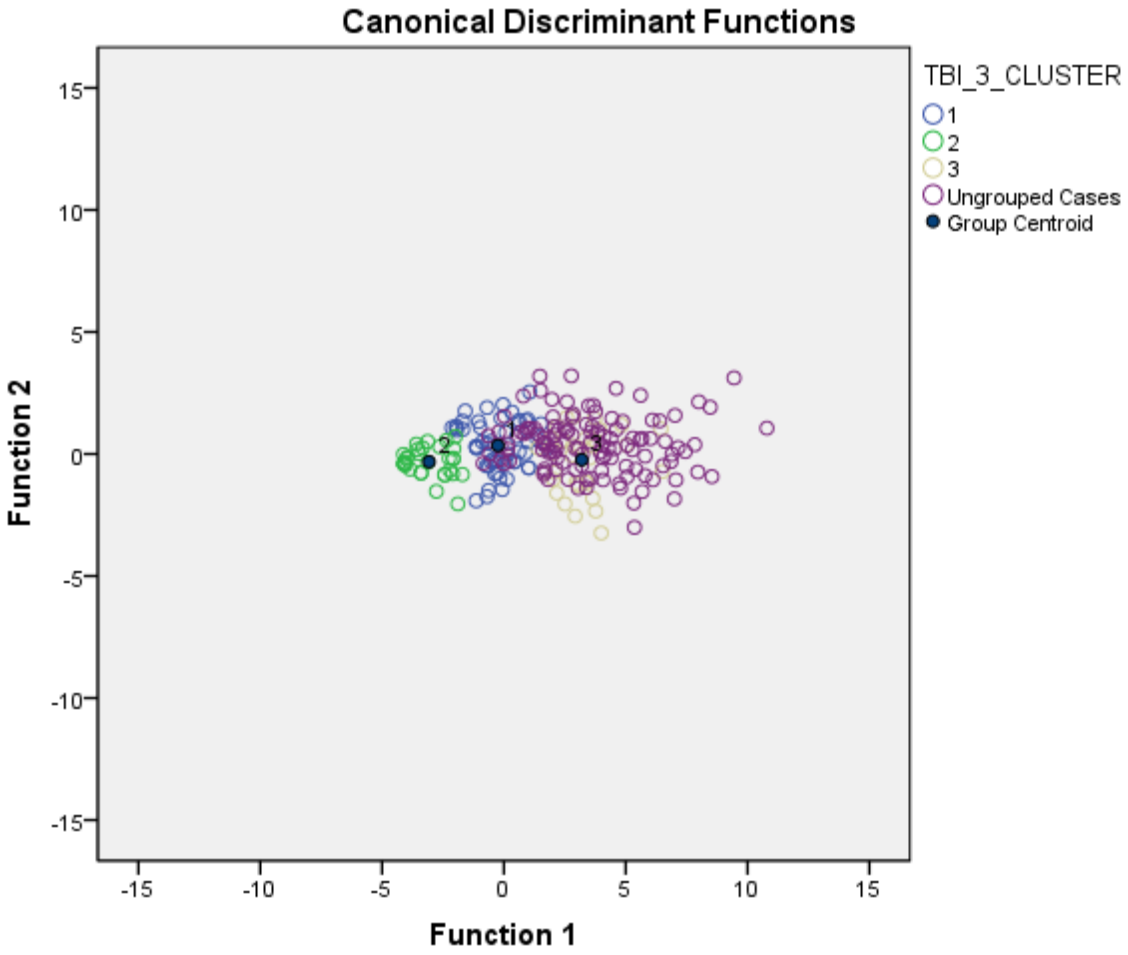


Figure 8.
Four-Cluster TBI solution, DFA of CTMT trials using Ward's Method.

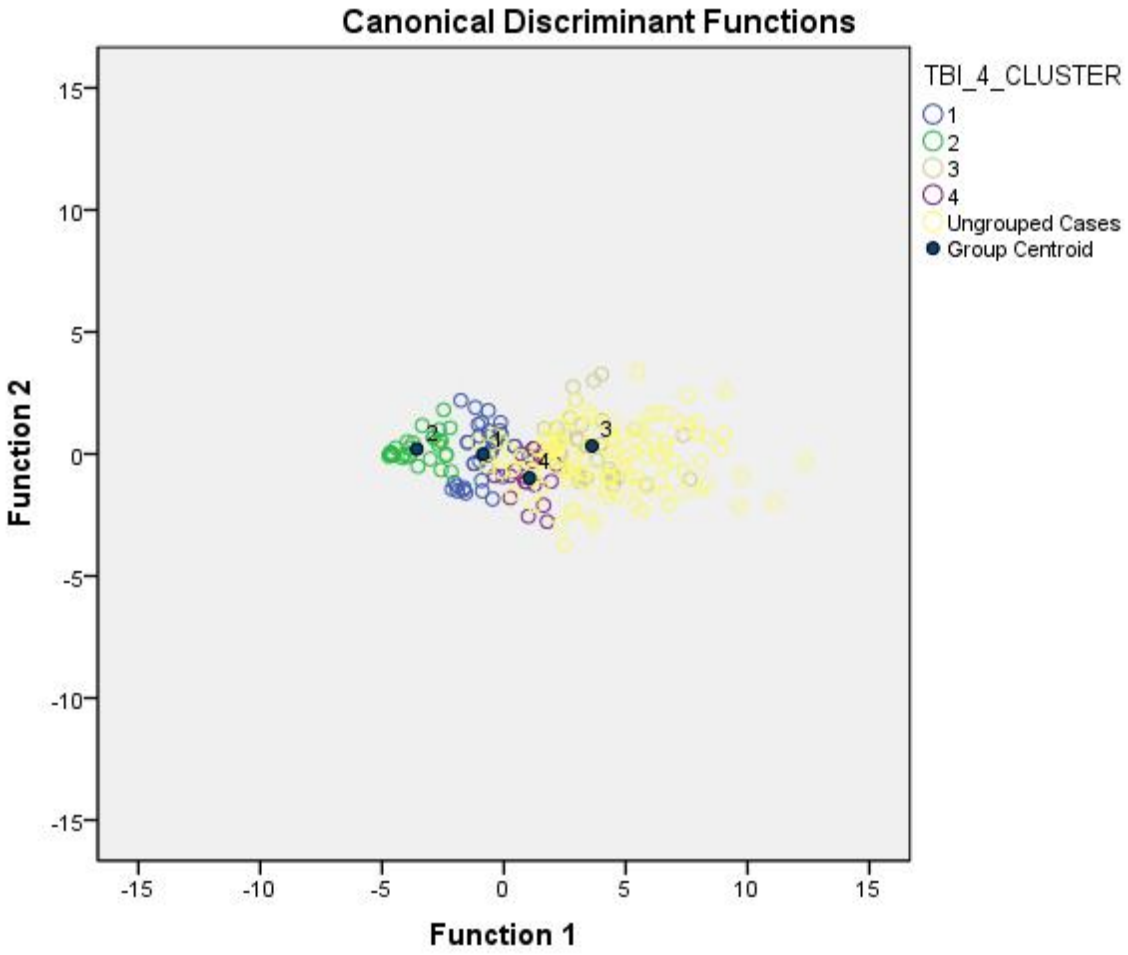


Figure 9.
Five-Cluster TBI solution, DFA of CTMT trials using Ward's Method.

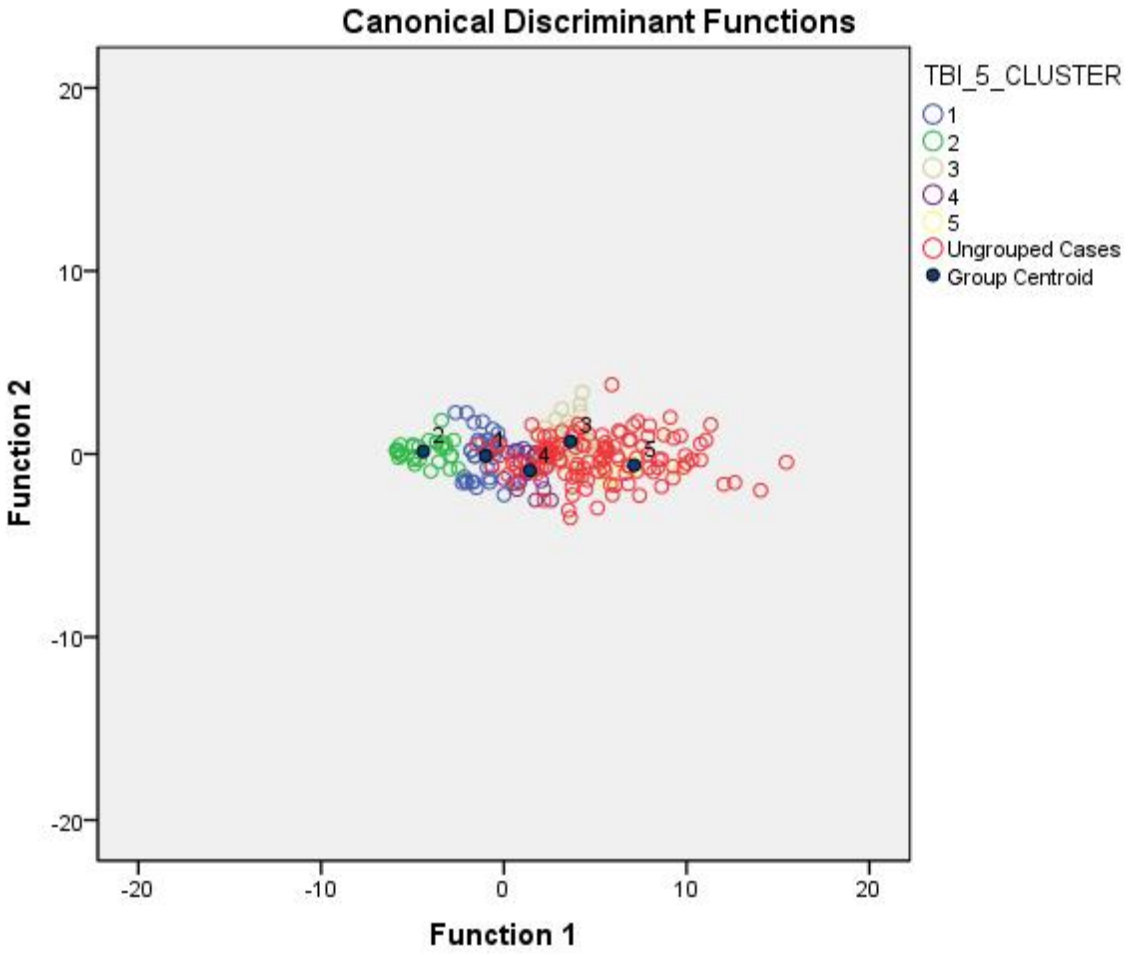


Figure 10.
Three-Cluster HC solution, DFA of CTMT trials using Ward's Method.

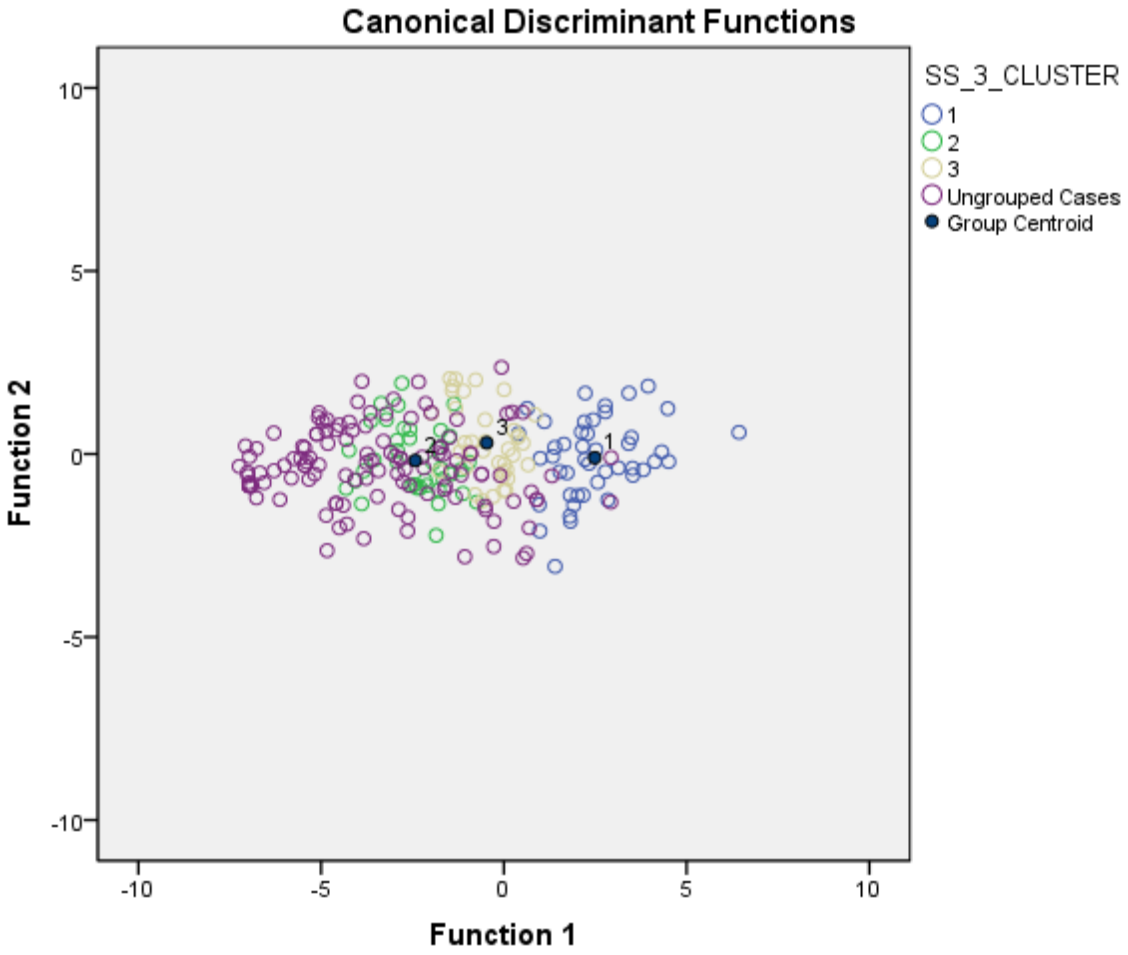


Figure 11.
Four-Cluster HC solution, DFA of CTMT trials using Ward's Method.

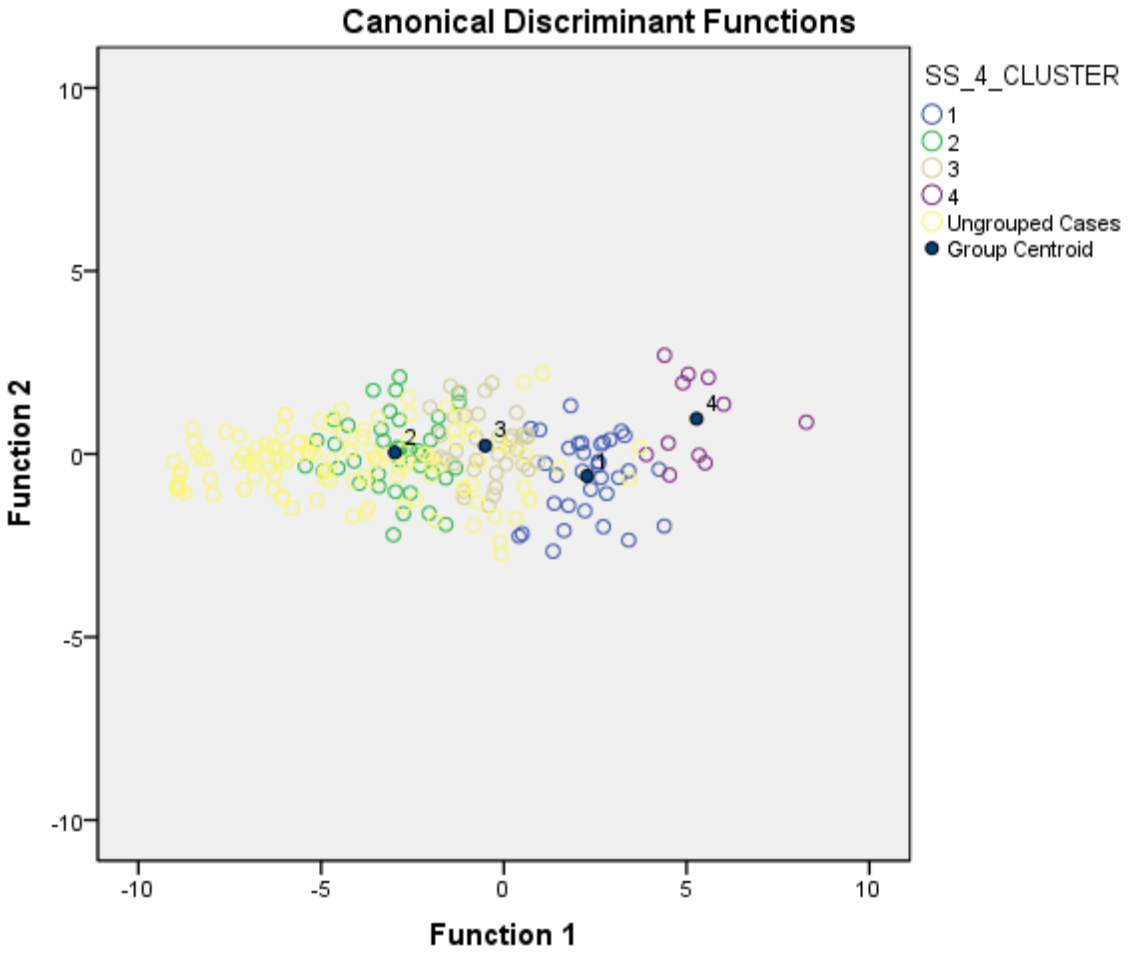


Figure 12.
Five-Cluster HC solution, DFA of CTMT trials using Ward's Method.

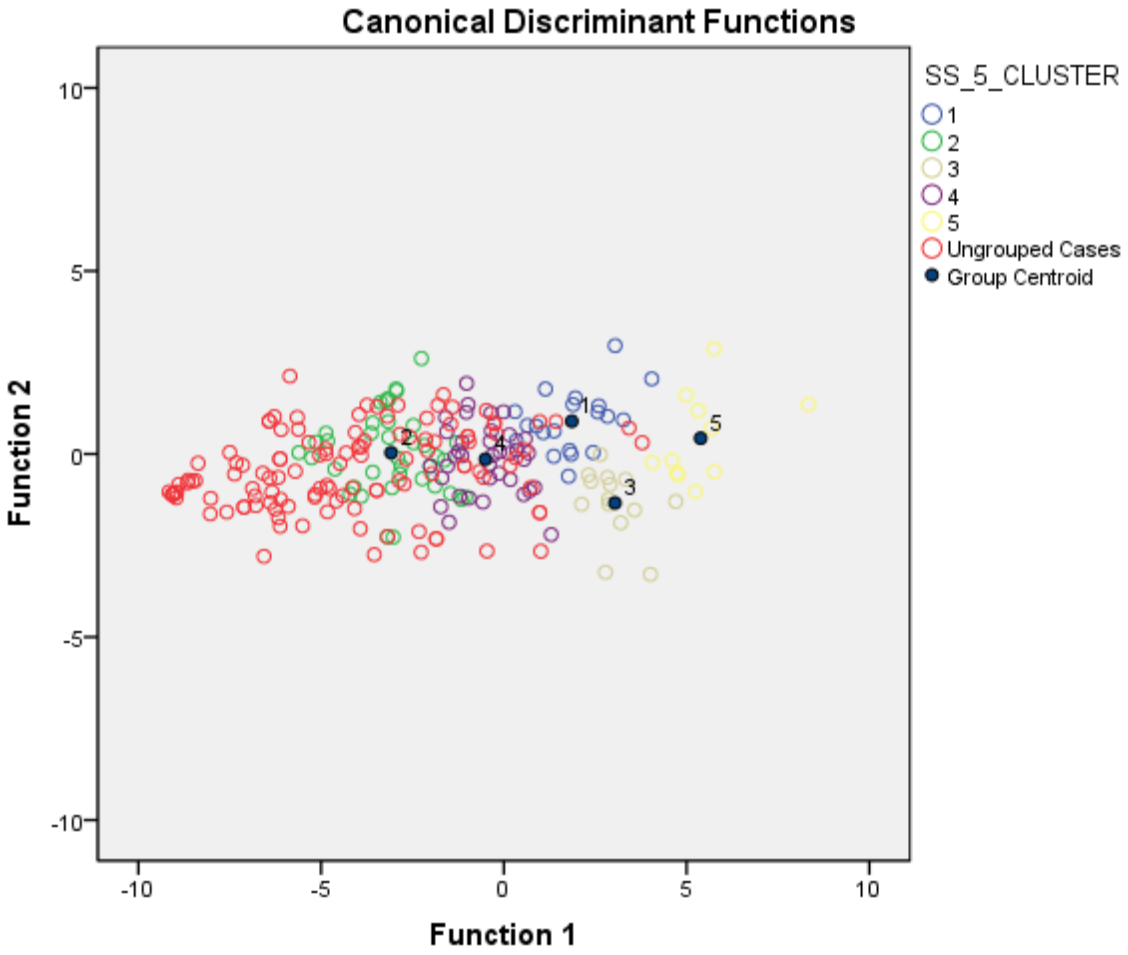


Figure 13.
Cluster Profiles of WAIS Indexes for the Three-Cluster Solution, TBI group: Scaled Scores and Ward's Method.

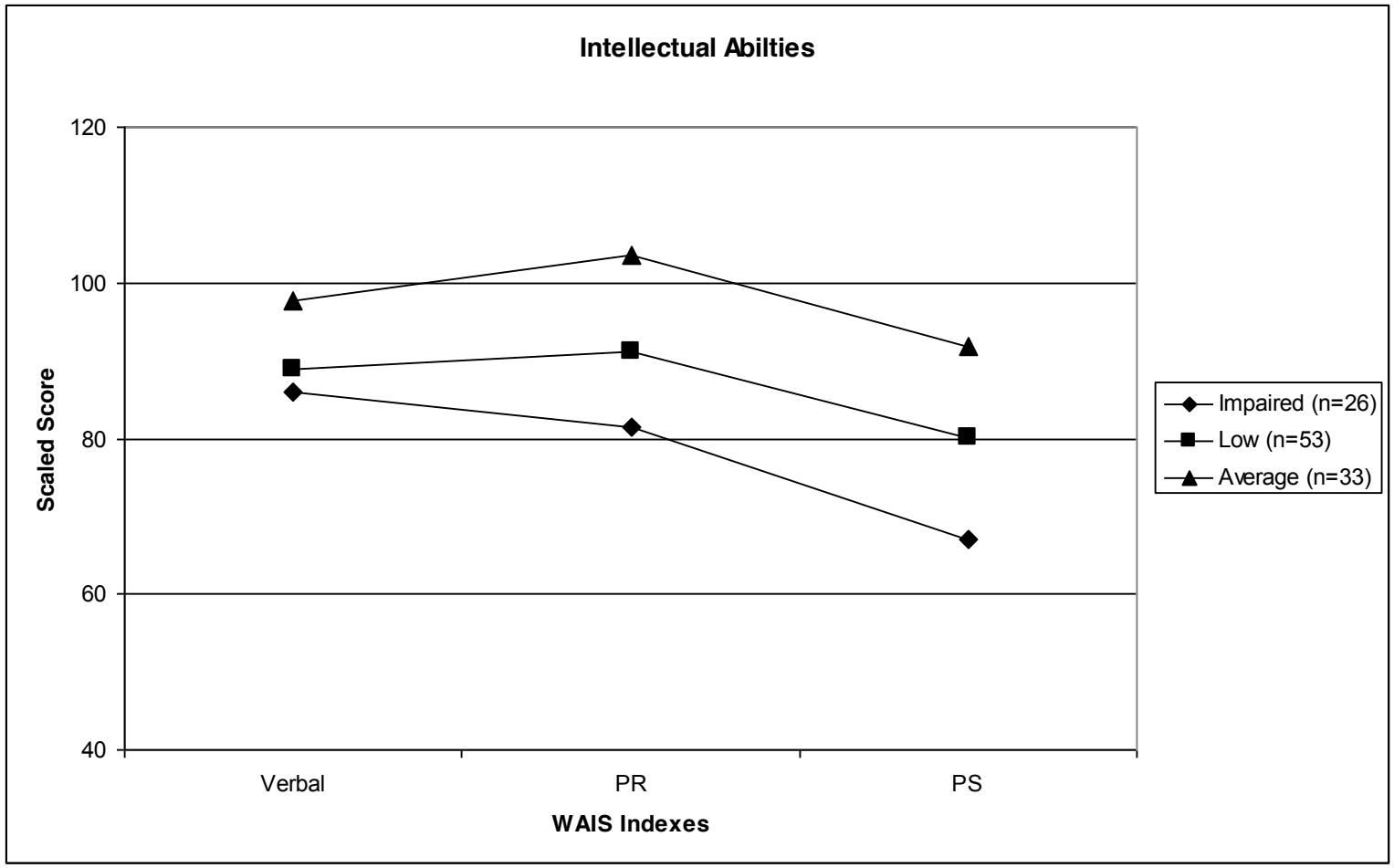


Figure 14.
Cluster Profiles of WAIS Indexes for the Five-Cluster Solution, TBI group: Scaled Scores and Ward's Method.

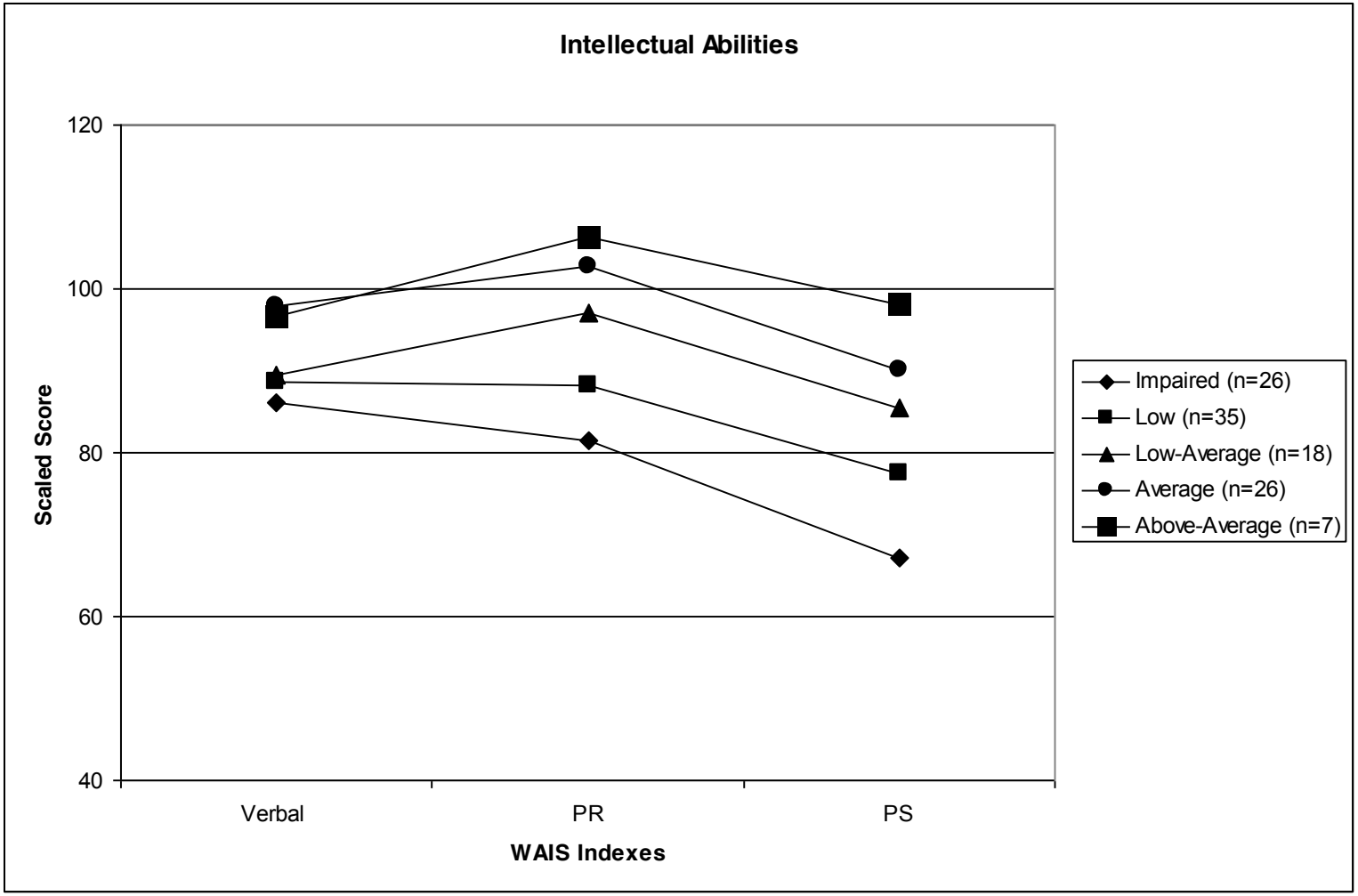


Figure 15.
Cluster Profiles of WJ-III-ACH Indexes for the Three-Cluster Solution, TBI group: Scaled Scores and Ward's Method.

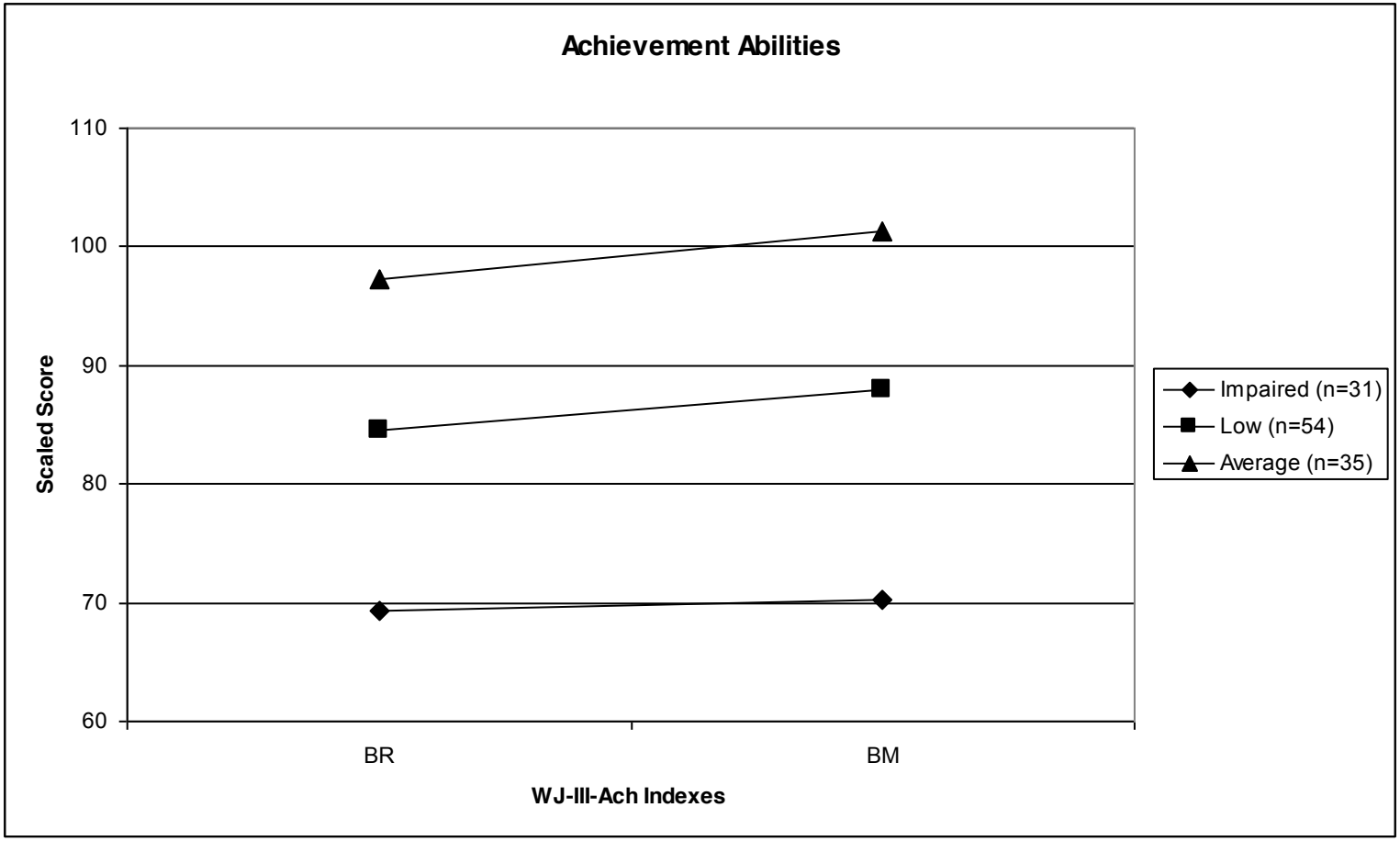


Figure 16.
Cluster Profiles of WJ-III-ACH Indexes for the Five-Cluster Solution, TBI group: Scaled Scores and Ward's Method.

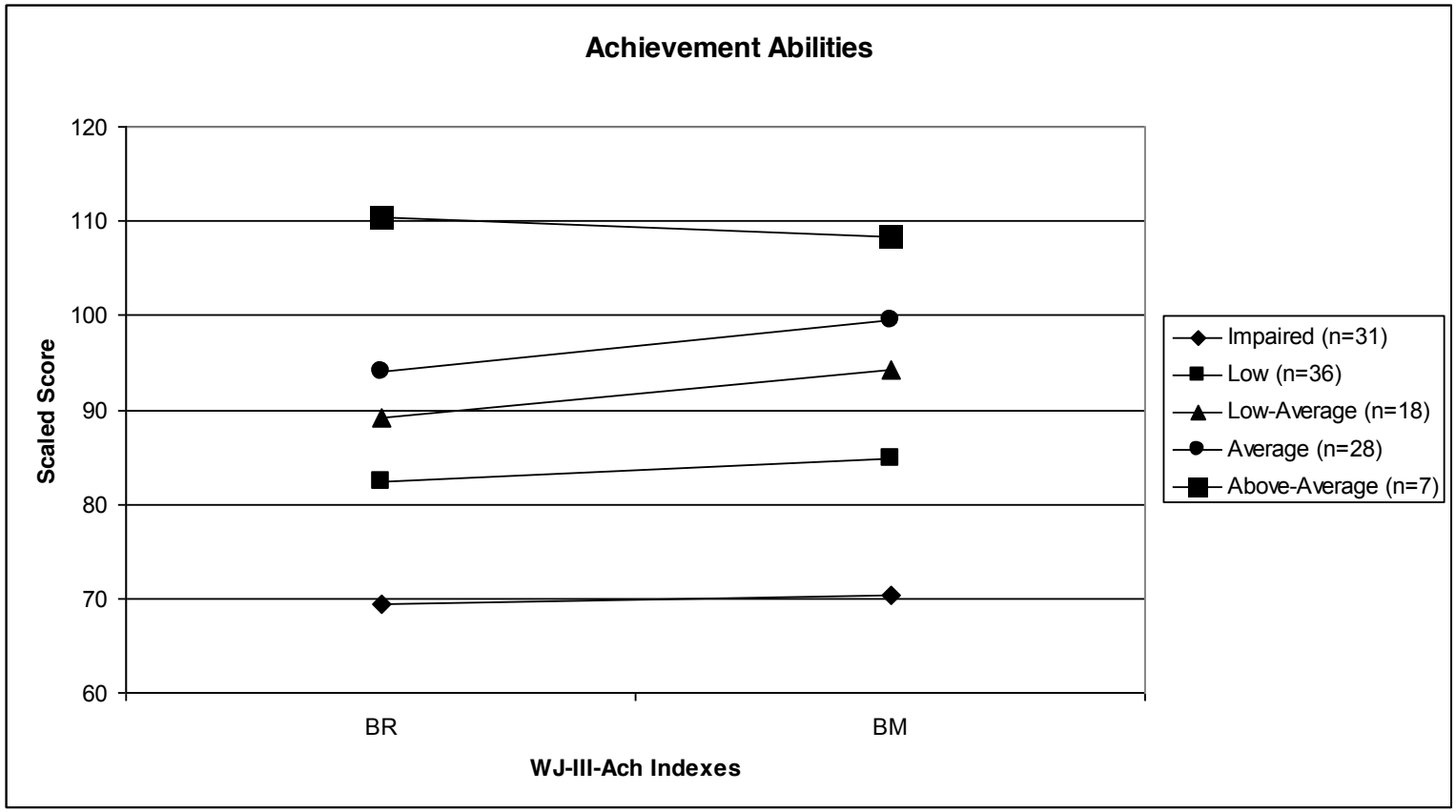


Figure 17.
Cluster Profiles of TOMAL Indexes for the Three-Cluster Solution, TBI group: Scaled Scores and Ward's Method.

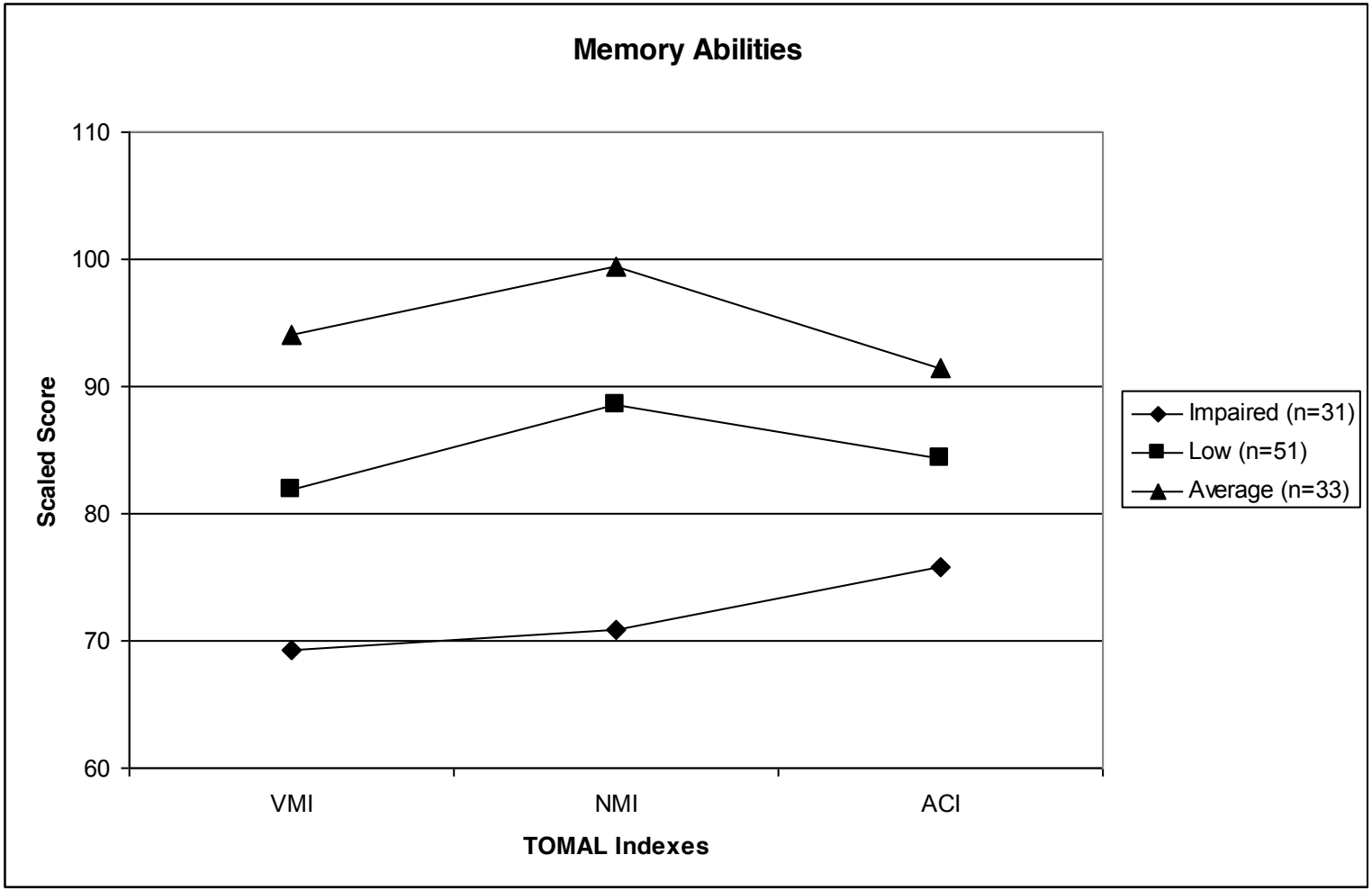


Figure 18.
Cluster Profiles of CPT Indexes for the Three-Cluster Solution, TBI group: Scaled Scores and Ward's Method.

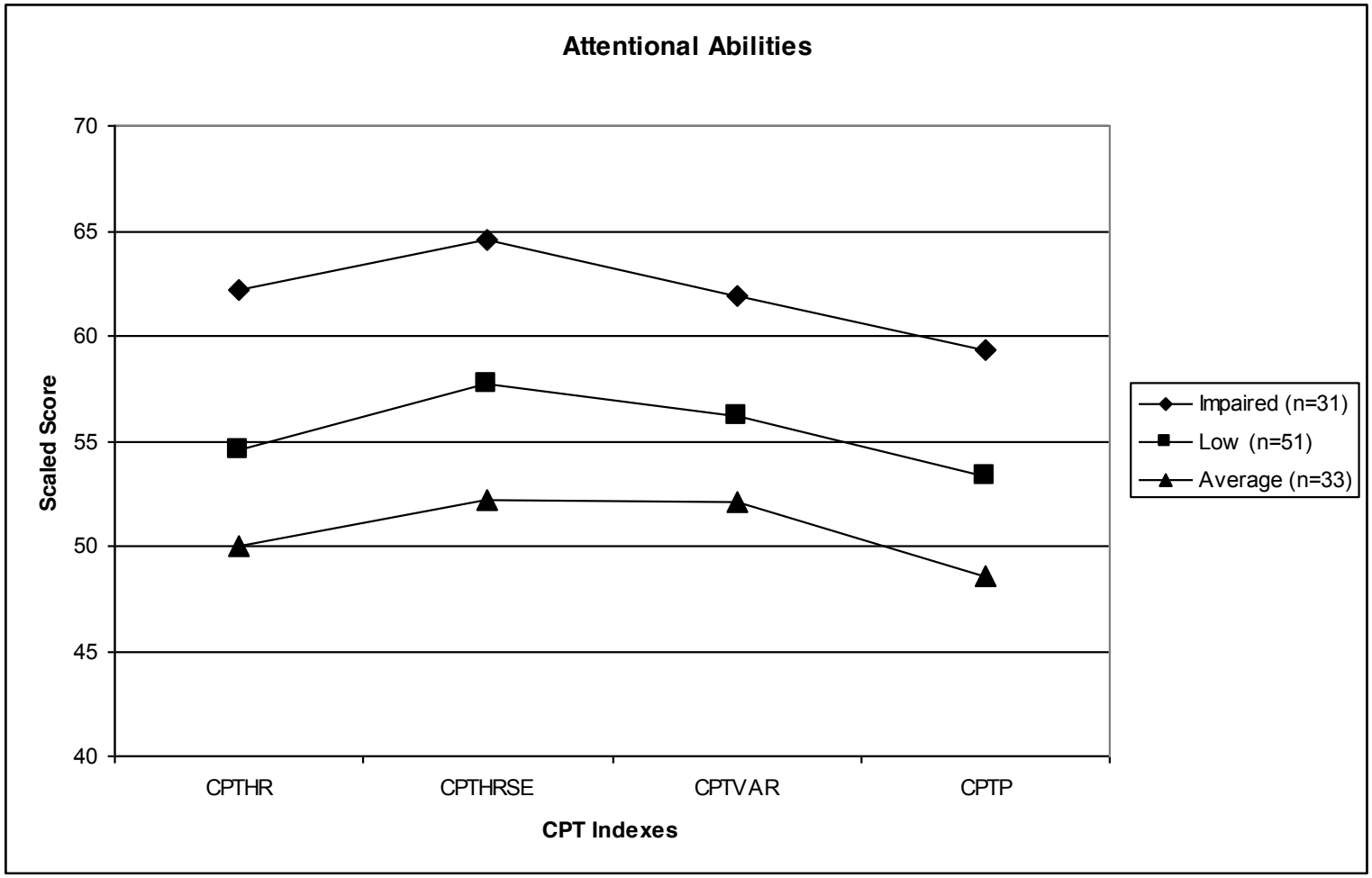


Figure 19.
Cluster Profiles of Receptive Language Indexes, Three-Cluster Solution, TBI group: Scaled Scores and Ward's Method.

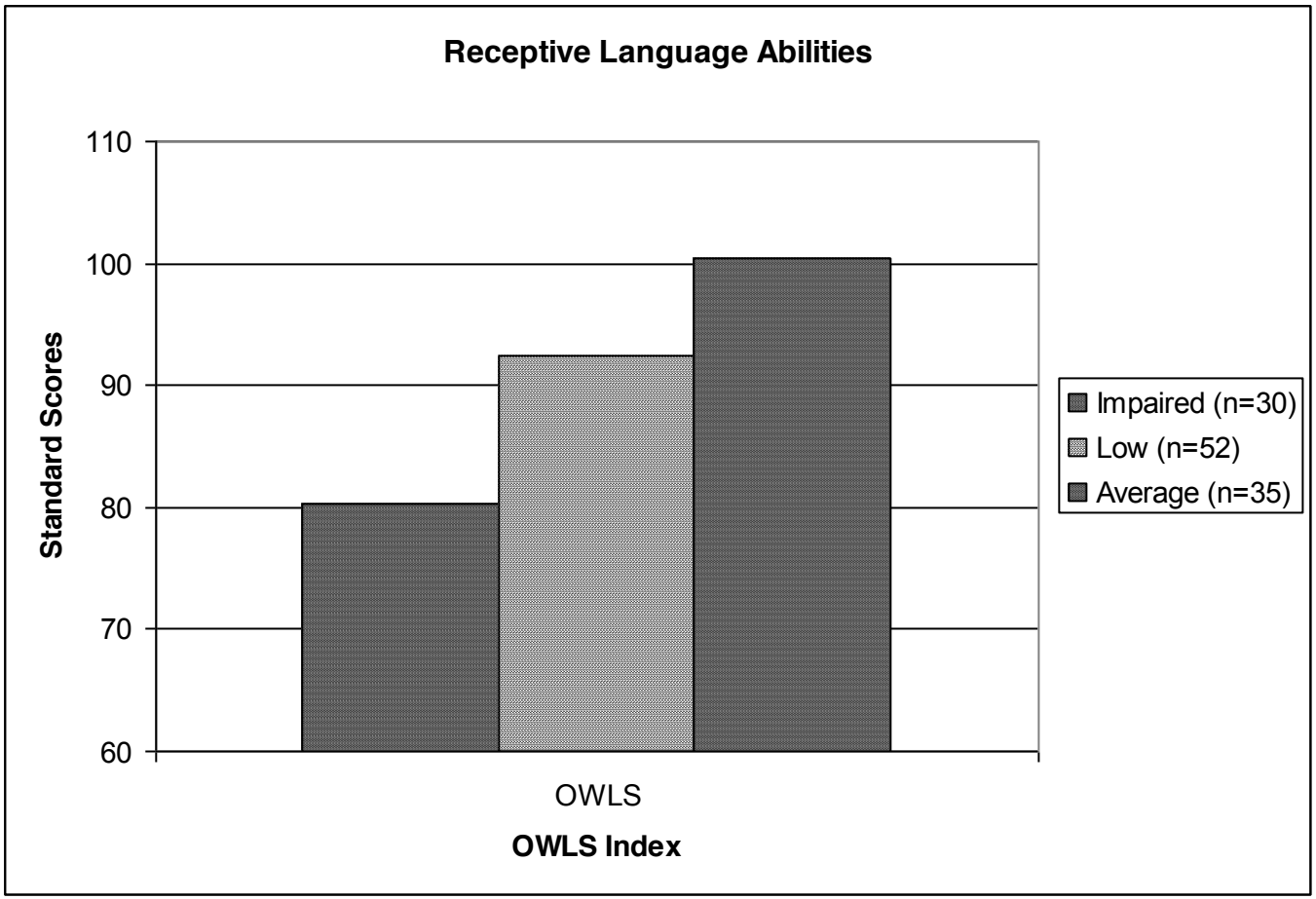


Figure 20.
Cluster Profiles of Fine Motor Ability, Three-Cluster Solution, TBI group: Ward's Method.

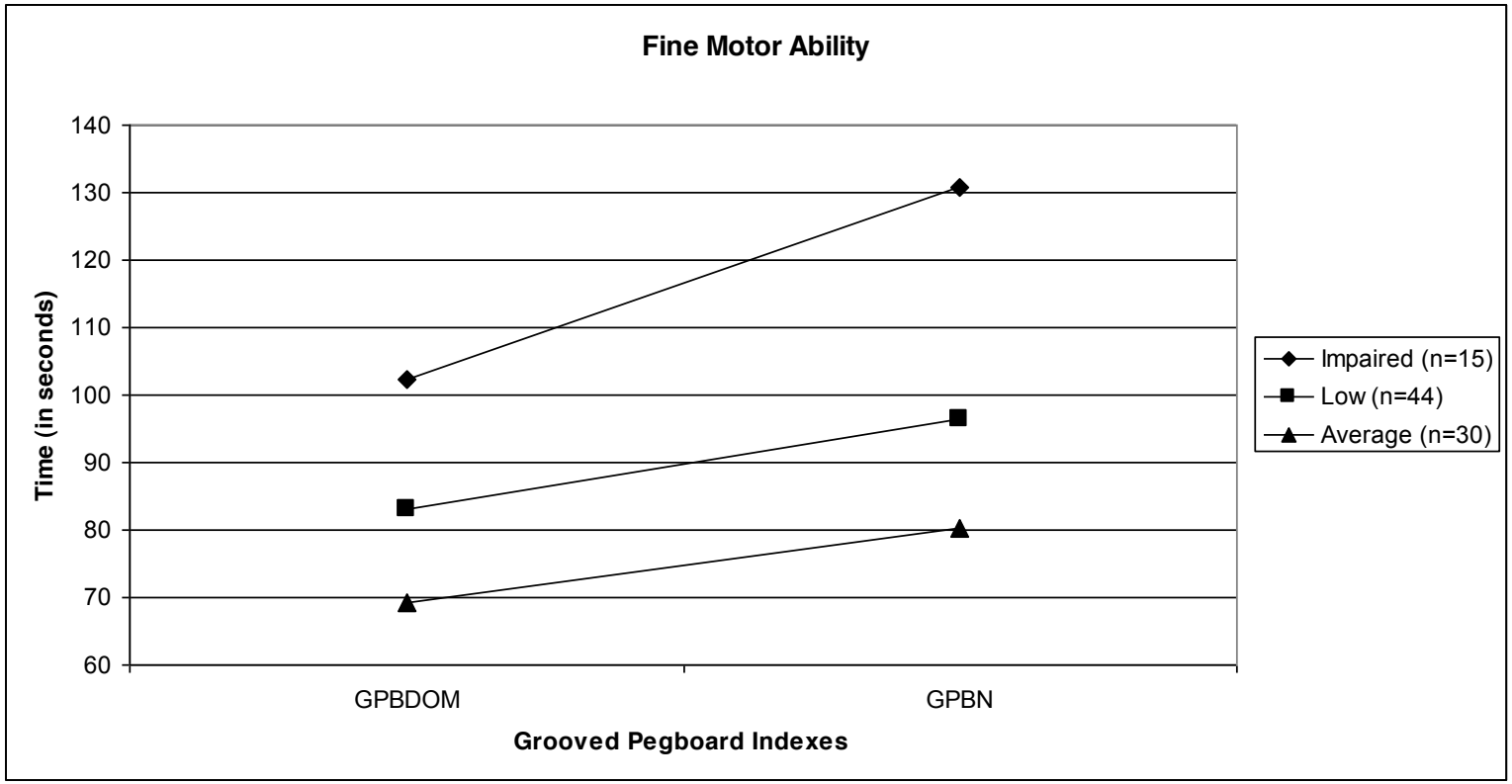


Figure 21.
Cluster Profiles of TOMAL Indexes for the Three-Cluster Solution, TBI group: Scaled Scores and Ward's Method.

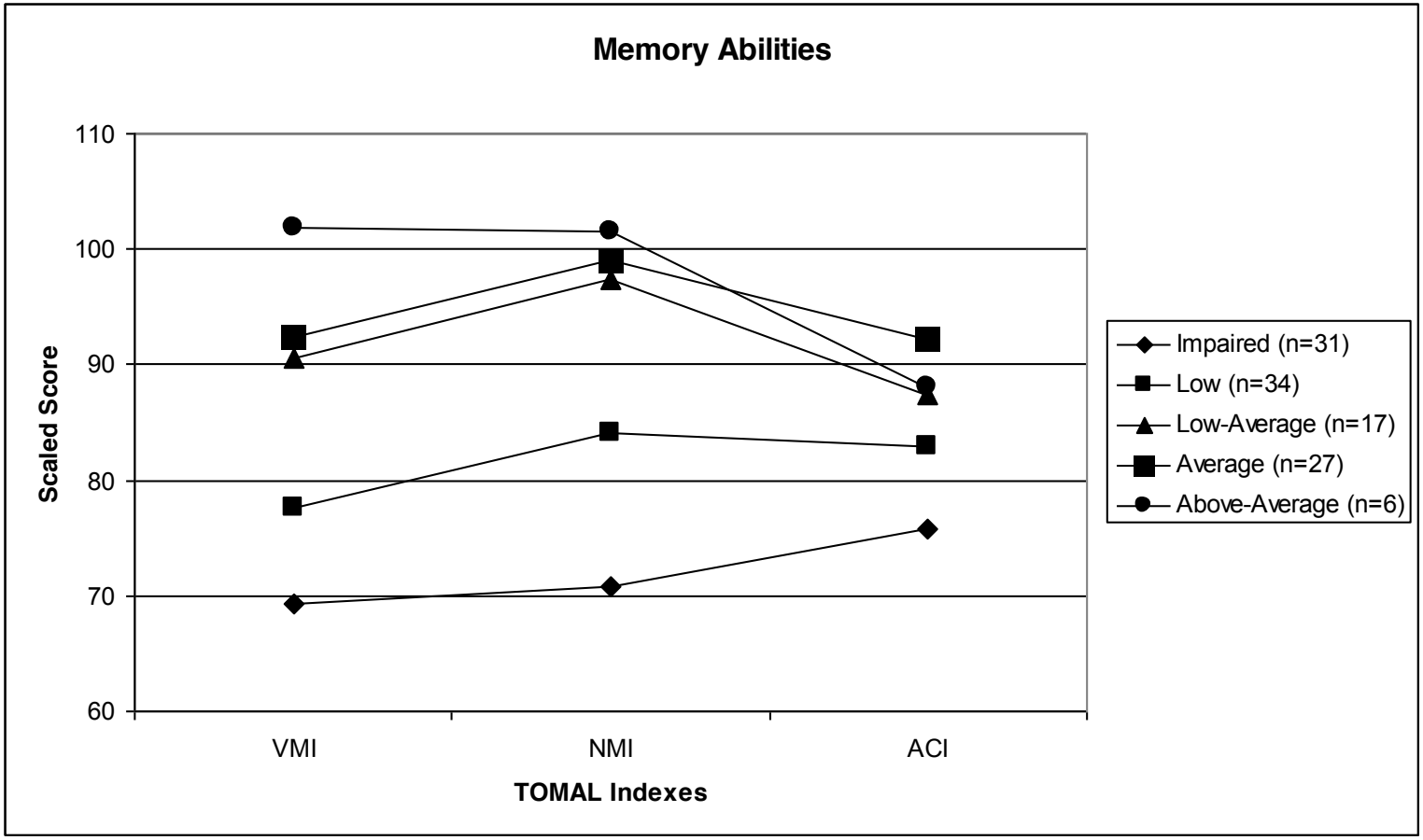

Memory Abilities
110
100
90
80
70
60
Scaled Score
VMI
NMI
ACI
TOMAL Indexes
Impaired (n=31)
Low (n=34)
Low-Average (n=17)
Average (n=27)
Above-Average (n=6)

Figure 22.

Cluster Profiles of CPT Indexes, Five-Cluster Solution, TBI group: Scaled Scores and Ward's Method.

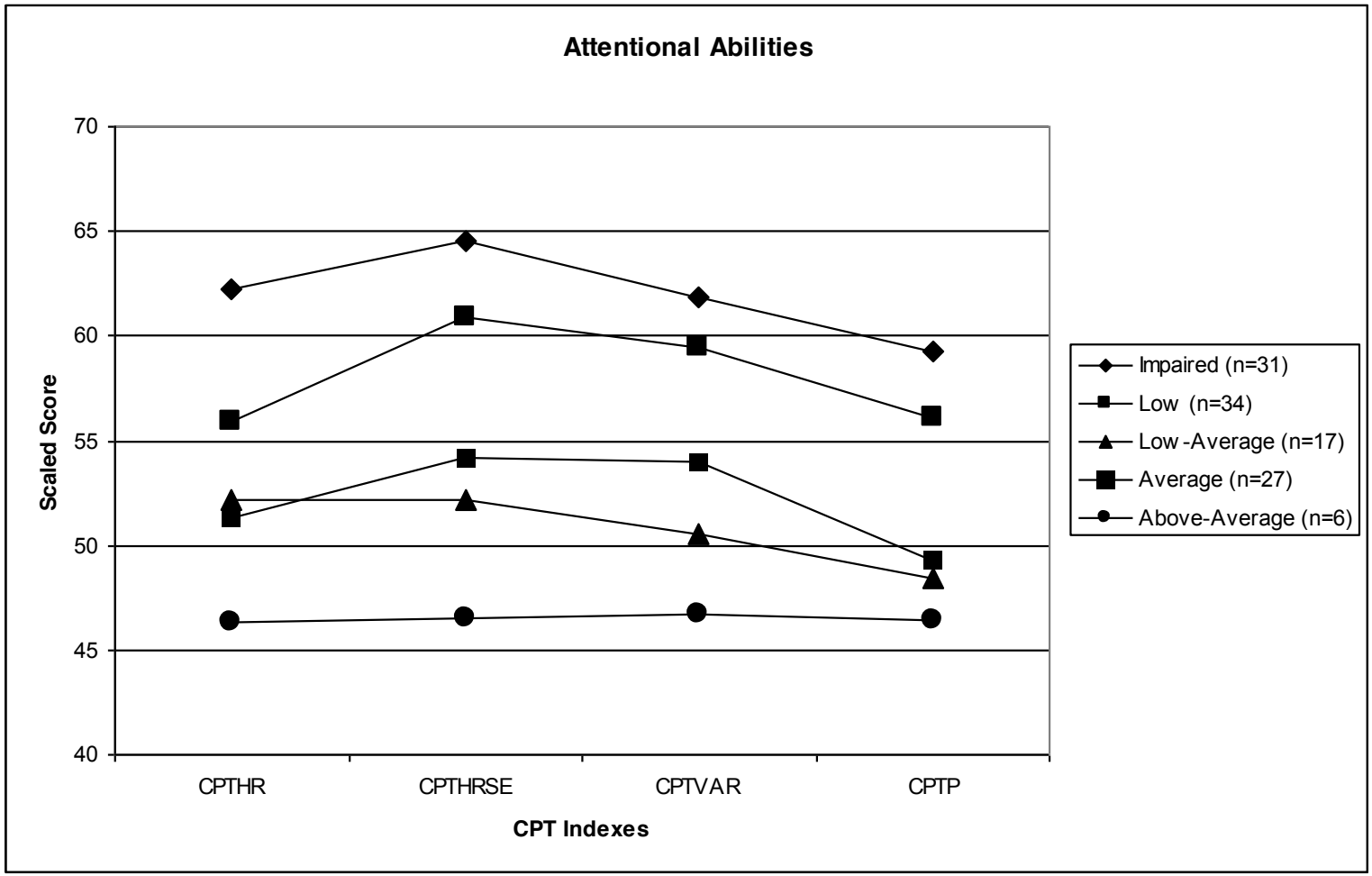


Figure 23.
Cluster Profiles of OWLS Receptive Language, Five-Cluster Solution, TBI group: Scaled Scores and Ward's Method.

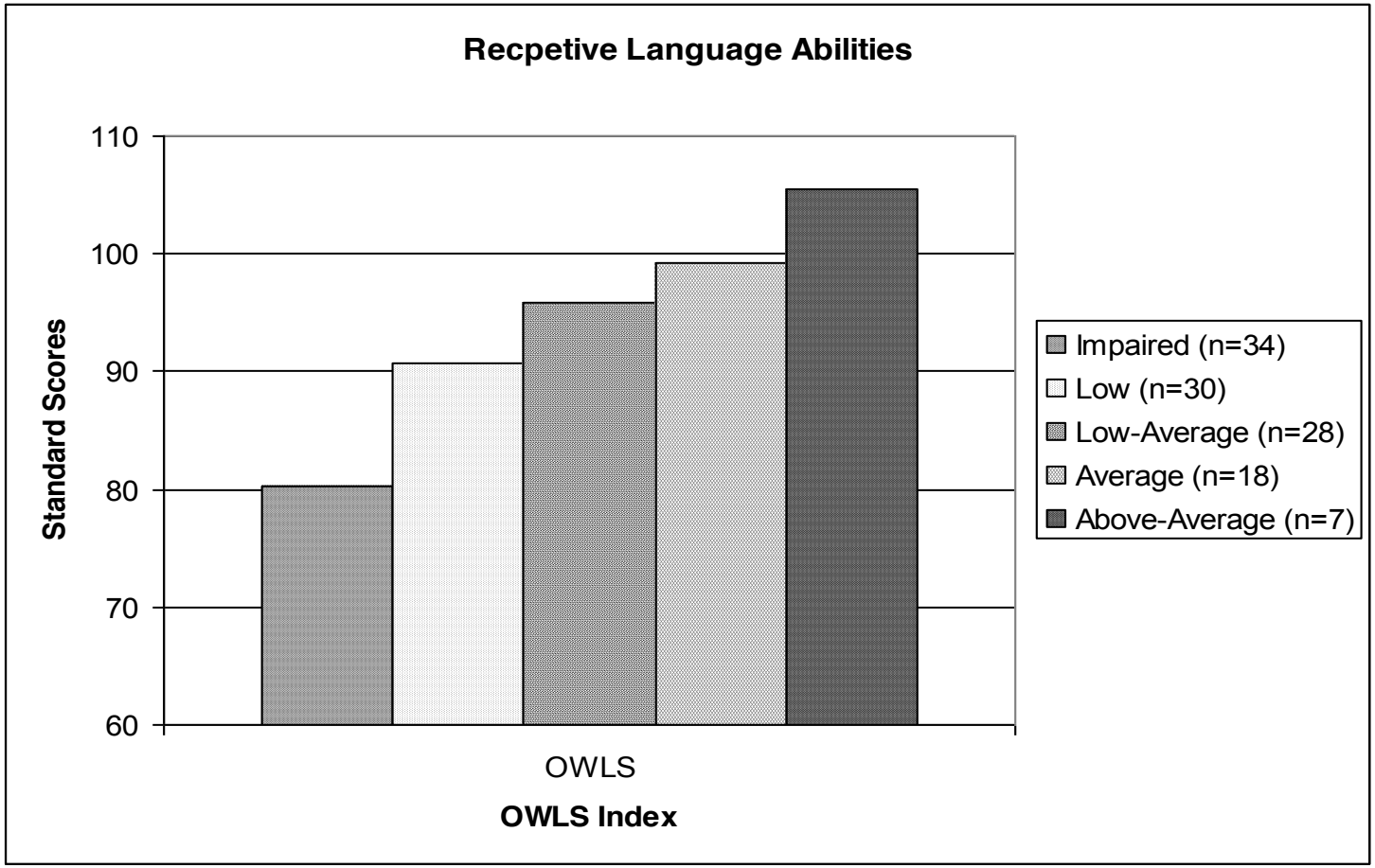


Figure 24.

Cluster Profiles of Fine Motor Ability, Five-Cluster Solution, TBI group: Ward's Method.

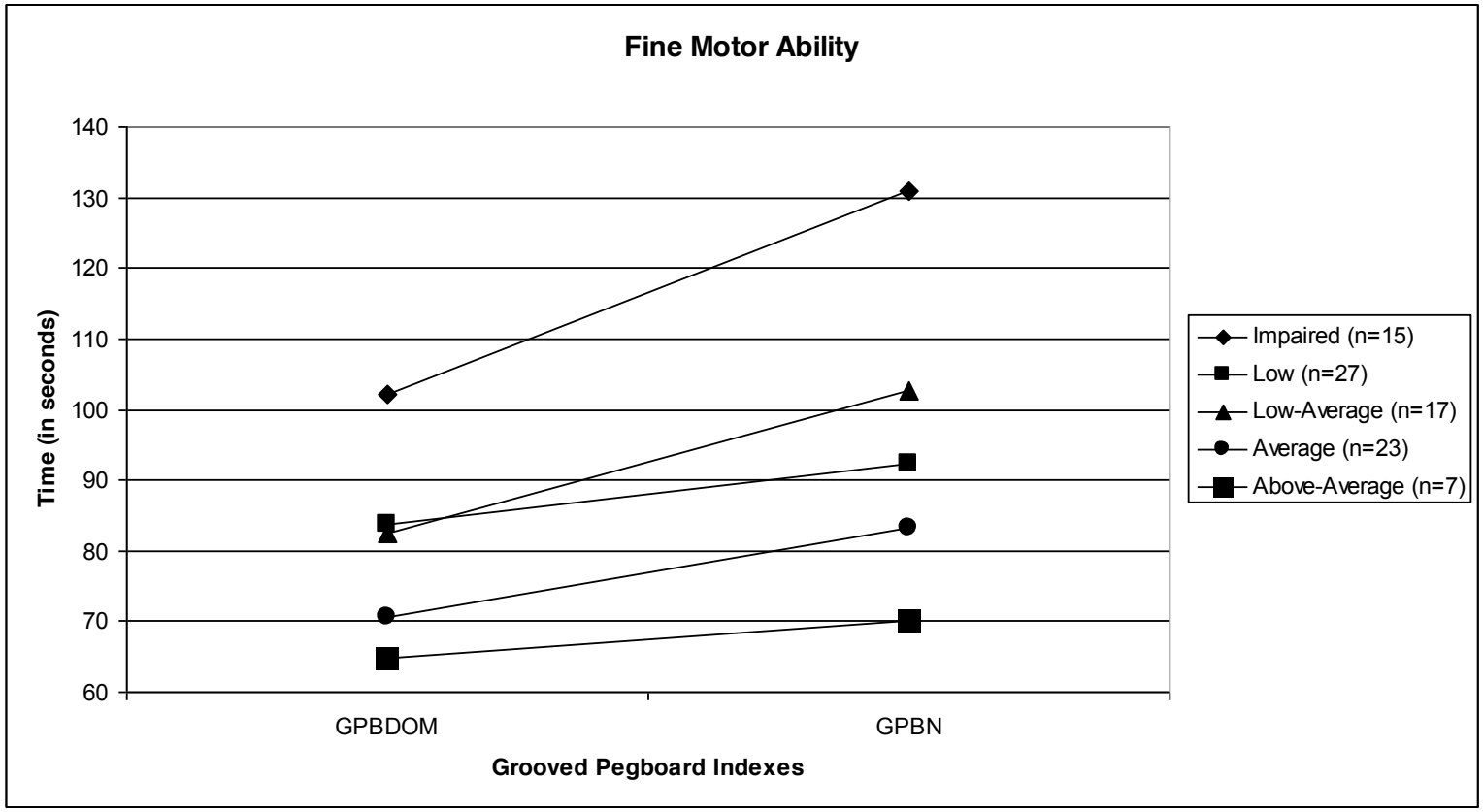
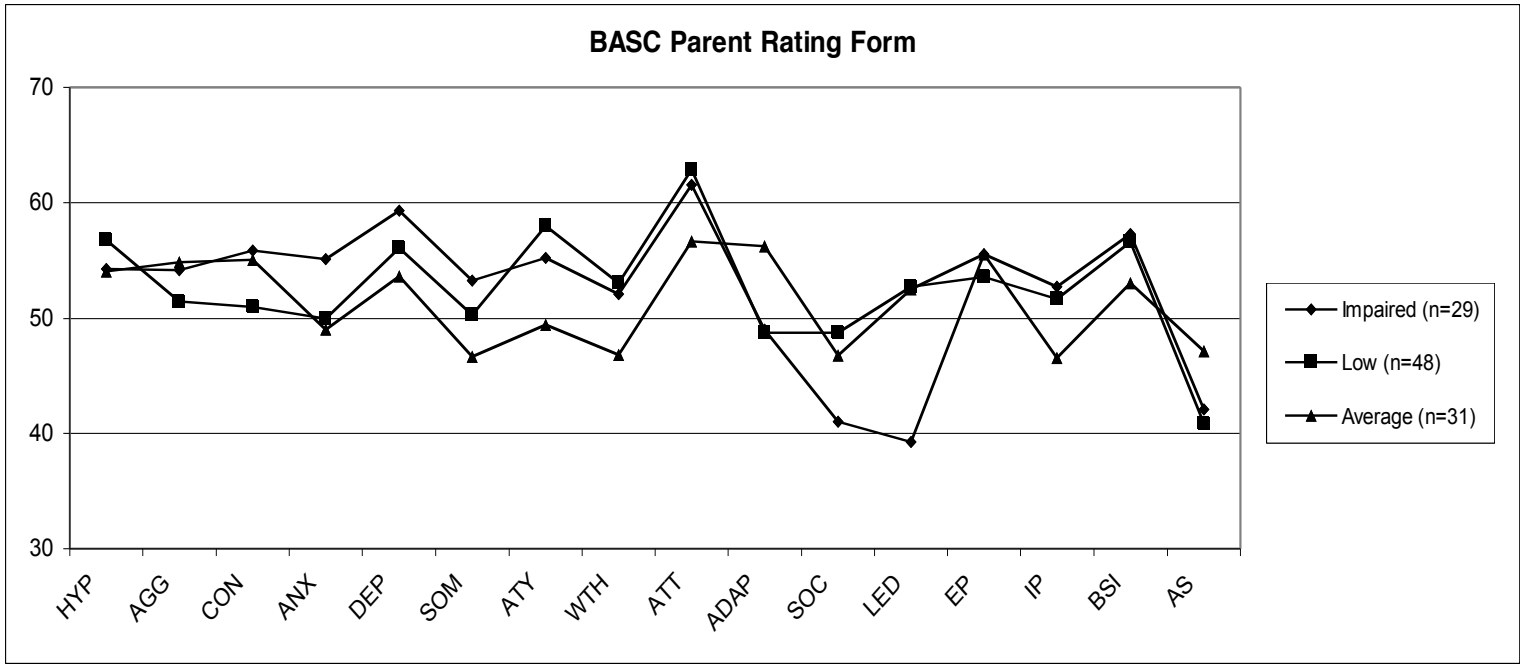


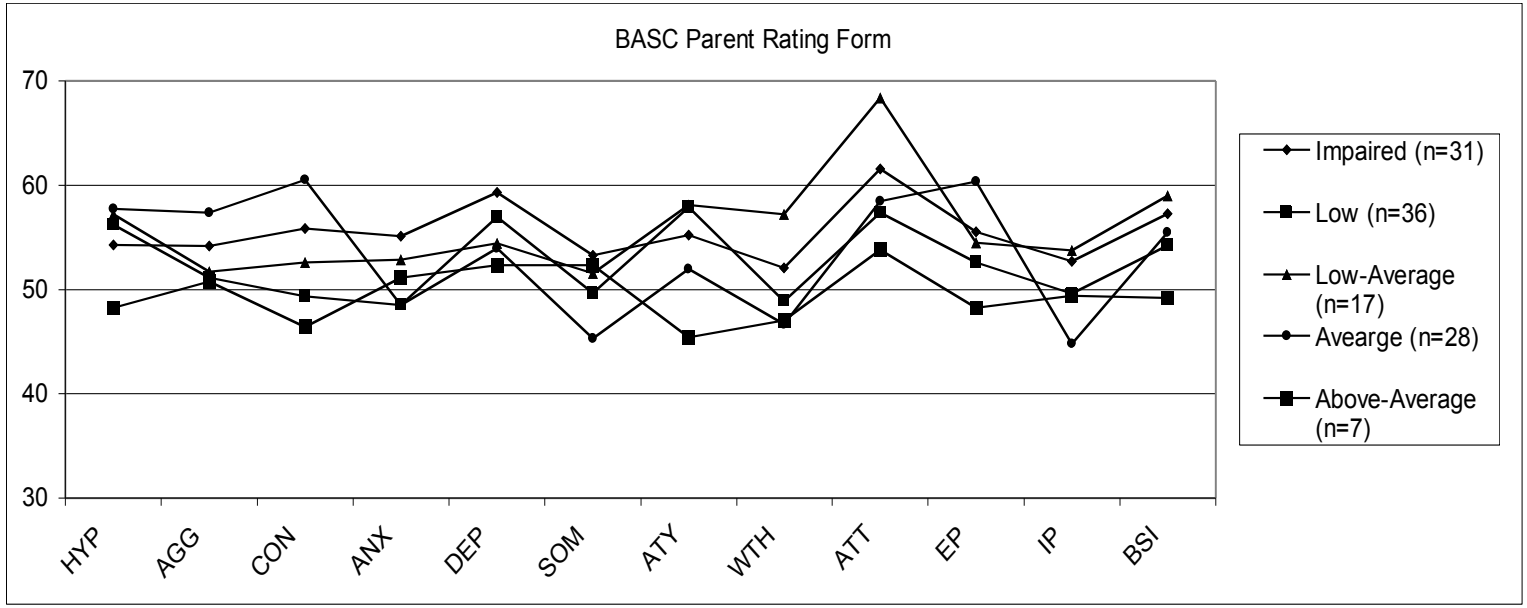
Figure 25.

Behavioral Assessment System for Children, PRS scores, Three-cluster solution, TBI group.



Note. HYP = Hyperactivity; AGG = Aggression; CON = Conduct Problems; ANX = Anxiety; DEP = Depression; SOM = Somatization; ATY = Atypicality; WTH = Withdrawal; ATT = Attention Problems; ADAP = Adaptability; SOC = Social Skills; LED = Leadership; EP = Externalizing Problems Index; IP = Internalizing Problems Index; BSI = Behavioral Symptoms Index; AS = Adaptive Skills Index.

Figure 26.
Behavioral Assessment System for Children, PRS scores, Five-cluster solution, TBI group.



Note. HYP = Hyperactivity; AGG = Aggression; CON = Conduct Problems; ANX = Anxiety; DEP = Depression; SOM = Somatization; ATY = Atypicality; WTH = Withdrawal; ATT = Attention Problems; ADAP = Adaptability; SOC = Social Skills; LED = Leadership; EP = Externalizing Problems Index; IP = Internalizing Problems Index; BSI = Behavioral Symptoms Index; AS = Adaptive Skills Index

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Weintraub, D.M., Ramage, E.M., Sutton, G., **Rangdahl, E.N.**, Boren, A., Pasinksi, A.C., Thaler,N., Haderlie, M., Allen, D.N., & Snyder, J.S. (submitted). Auditory stream segregation impairments in schizophrenia. Submitted to Cerebral Cortex.

Weintraub, D., Ramage, E., Sutton G., **Ringdahl, E.**, Boren, A., Pasinski, A., Thaler, N., Haderlie, M., Allen, D., Snyder, J. (In Press). Auditory stream segregation deficits in schizophrenia: Behavioral and event-related potential evidence. *American Journal of Psychiatry, 1-24*.

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