EXECUTIVE FUNCTIONING IN CHILDREN AND ADOLESCENTS WITH TRAUMATIC BRAIN INJURIES: UTILIZATION OF THE COMPREHENSIVE TRAIL MAKING TEST

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

IN THE GRADUATE SCHOOL OF THE

TEXAS WOMAN'S UNIVERSITY

COLLEGE OF ARTS AND SCIENCES

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MAY 2008

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April 3, 2008

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I am submitting herewith a dissertation written by Wendi Leigh Bauman entitled "Executive Functioning in Children and Adolescents with Traumatic Brain Injuries: Utilization of the Comprehensive Trail Making Test." I have examined this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy with a major in School Psychology.

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DEDICATION

For my mom, whose faithful prayers and loving support has been my companion along this journey. For my siblings, Andrew, Nathan and Julie, whose humor and encouragement made me laugh when I needed it. And for my fiancé, Gordon, who has patiently listened to my trials. I look forward to walking through life together by your side.

ACKNOWLEDGMENTS

A task of this magnitude could not have been accomplished without the assistance and encouragement of many individuals. The book of Ecclesiates says that "Two are better than one because they have a good return for their labor. For if either of them falls, the one will lift up his companion." I have been blessed with many "companions" who have lifted me up along this journey through graduate school. First of all, my gratitude extends to my Lord and Savior Jesus Christ. For to Him I am grateful for the gift of life and the ability to accomplish this task. My purpose in life is to know Him better and to make Him known. Secondly, I am thankful for my family and friends who have literally lifted me up when I thought I may not make it through. Your thoughts, prayers, and words of encouragement have sustained me along the way.

My appreciation extends to my dissertation committee members. I am thankful for Daniel Miller, Ph.D., Denise Maricle, Ph.D., and Kathy DeOrnellas, Ph.D. for their guidance and support at each step. I am grateful for the assistance provided by Daniel Allen, Ph.D. through his suggestions and statistical knowledge. My thanks go out to Joan Mayfield, Ph.D. for the use of her data and investment of her time and resources. I also thank Cecil Reynolds, Ph.D. for allowing me to use the normative data of the CTMT. Without each one of you, this task could not have been accomplished. Thank you.

ABSTRACT

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EXECUTIVE FUNCTIONING IN CHILDREN AND ADOLESCENTS WITH TRAUMATIC BRAIN INJURIES: UTILIZATION OF THE COMPREHENSIVE TRAIL MAKING TEST

MAY 2008

Traumatic brain injuries have frequently been referred to as the "silent epidemic." The term "silent" is used to describe the often invisible, yet detrimental effects a traumatic brain injury (TBI) may cause. Increasing prevalence rates have led to 1.4 million TBIs occurring each year in the United States, with an estimated 90,000 individuals enduring a permanent disability due to the TBI. Within children and adolescents, TBIs are the leading cause of death and disability.

A childhood TBI often results in life-long cognitive impairments frequently seen in basic psychological processes such as attention, perception, language, memory, and executive functioning skills. Of these vital skills, executive dysfunction has been described as the most debilitating, long-term deficit resulting from a TBI. Despite the epidemic proportions and the long-term effects, few studies have utilized a developmentally appropriate, standardized measure to assess executive functioning within a pediatric TBI population. The purpose of this study was to compare executive functioning, as measured by the Comprehensive Trail Making Test (CTMT), of children and adolescents who have sustained a TBI to a non-injured control group to determine the nature and extent of differences between groups.

The participants included 160 children and adolescents between the ages of 11- and 19-years-old. Eighty of the participants had sustained a head injury and 80 were randomly matched on age and gender from the standardization sample of the CTMT. Initial data analysis utilized a univariate ANOVA which demonstrated significant differences between groups on the CTMT Composite Index. Secondly, repeated measures MANOVAs indicated differences between the clinical and control groups on each CTMT trail and on combination of trails, but no within group differences. Finally, the results of the TBI sample were examined to confirm the findings of a two factor model evident in the CTMT standardization sample. Results revealed that a single factor model was a better fit for the present sample of TBI participants. The findings of this study enhance the understanding of the substantial impact a pediatric TBI has on executive functioning. The implications of these results provide additional interventions for practitioners and educators as they work with this population.

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CHAPTER I

INTRODUCTION

The “silent epidemic” of traumatic brain injuries is covertly stealing the developing minds of the next generation. Traumatic Brain Injuries (TBIs) are frequently referred to as “silent” due to the damaging, yet often invisible long-term effects demonstrated through memory loss, attentional disorders, and executive functioning deficits (Langlois, Rutland-Brown, & Thomas, 2006). The term “epidemic” refers to the impact that TBIs have on the population, as well as the increasing percentage of individuals who experience significant cognitive functioning deficits as the result of a brain injury. At least 1.4 million TBIs occur each year in the United States resulting in 50,000 deaths and 235,000 hospitalizations (Langlois et al.). Of those that sought medical help, the leading causes of TBIs were falls, motor-vehicle accidents, and assaults. The National Center for Injury Control and Prevention approximates that each year an estimated 80,000 to 90,000 individuals have a permanent disability as the result of sustaining a TBI (Langlois et al.). In children and adolescents, TBIs are the leading cause of death and disability (Jankowitz & Adelson, 2006). Children 14-years-old and younger experience an average of 475,000 brain injuries every year. In young children, falls account for the highest percentage of TBIs, while among adolescents motor vehicle accidents cause the largest number of TBI related injuries (Langlois et al.).

A childhood TBI often results in life-long deficits. Persistent cognitive impairments affect basic psychological processes such as attention, perception, language, memory, and abstract reasoning (Farmer, Clippard, Luehr-Wiemann, Wright, & Owings, 1997). Sub-component systems are oftentimes also affected which impair working memory, long-term memory, response modalities, and executive functions such as initiating, organizing, and executing planned actions (Farmer et al.).

Several factors affect the manifestation of these deficits. The age at injury, location and severity of the injury, as well as pre-injury functioning, all affect the extent of the long-term deficits. Depending on these factors, cognitive impairments often persist and affect academic progress as the child matures. Unfortunately, due to the subtle nature of the deficits, deficiencies may not be readily apparent on standardized measures of intelligence (Ylvisaker & DeBonis, 2000). Typically, a common TBI profile will reflect stronger verbal abilities or performance on language-based tasks. However, when novel tasks are presented that require problem-solving abilities, processing speed, and organization, deficits are more clearly evident (Farmer et al., 1997).

Statement of the Problem

Because of the limitations of generalized measures of intelligence for assessing TBI, it is important to utilize tests sensitive to the effects of brain injury in children. Until recently, only a small number of measures were available to specifically address neuropsychological deficits after a brain trauma. Of these measures, few were validated and standardized for use with children. All too often test batteries for children were downward extensions of measures designed for adult populations. The NEPSY (Korkman, Kirk, & Kemp, 1998), and its subsequent revision the NEPSY-II (Korkman, Kirk, & Kemp, 2007), was the first developmental neuropsychological battery specifically designed for children. Instead of modifying an adult battery, the NEPSY-II factors in the effect development has on neuropsychological processes.

The NEPSY-II measures the subcomponents of complex neuropsychological processes including Executive Functioning, Language, Sensorimotor Functions, Visuomotor Processing, Memory and Learning, as well as Social Perception (Korkman et al., 2007). When utilizing the NEPSY-II with a TBI population, deficits are often seen across multiple areas. However, executive system impairment has been described by Ylvisaker and DeBonis (2000) as "the most debilitating disorder after TBI" (p. 35). Given the importance of executive functioning on daily living, academic success, and social interactions, it is imperative to accurately assess these deficits in children. Within the domain of executive functioning, the NEPSY-II examines strategic planning abilities, flexibility, and self-regulatory processes, as well as the sub-components within executive functioning of initiation, fluency, inhibition, and working memory (Kemp, 2007). The measurement of executive functioning with the NEPSY-II provides valuable insights; however, executive skills are one of six primary components assessed within the NEPSY-II. To allow for in-depth assessment of executive abilities, the Delis-Kaplan Executive Function System (D-KEFS) (Delis, Kaplan, & Kramer, 2001) was developed. This is the first comprehensive assessment specifically examining executive functioning. The D-

KEFS uses both verbal and non-verbal stimuli encompassed within a battery of nine independent tests designed to measure specific aspects of executive functioning (Delis et al.). The D-KEFS assesses skills related to executive functioning such as mental flexibility, verbal and visual fluency, behavioral initiation, concept formation, rule learning, and planning abilities (Delis et al.).

With the addition of the NEPSY-II and the D-KEFS, reliable and valid measures for assessing executive functioning in children have greatly improved. However, all too often outdated or poorly standardized measures designed for adults continue to be utilized with children. Also, clinicians may use portions of broader standardized adult batteries, such as the Halstead-Reitan (Reitan & Wolfson, 1985) and adapt them for use with children. The utility and psychometric validity of these portions have often not been validated for use with children. One popular measure, which has seen multiple variations, is Trails A and Trails B. Originally adapted from the Army Individual Test Battery (1944), Trails A entails the subject to connect consecutively numbered circles. In Trails B the individual must alternate between connecting letter and number sequences. Reitan (1971) combined Trails A and B to comprise The Trail Making Test (TMT). The TMT is used to assess a number of neurocognitive abilities including psychomotor speed, complex attention, visual scanning, and mental flexibility. It has been repeatedly demonstrated to be sensitive to brain injury in adults (Boll, Berent, & Richards, 1977; Espy & Cwik, 2004, Jaffe et al., 1993; Reitan, 1955, 1971). Reviews of the TMT indicate test-retest reliability coefficients around .60, which is in the low range for what is considered acceptable use for clinical diagnosis (Espy & Cwik, 2004). Reitan and Wolfson (1992) followed up and published a TMT for use with children. Neyens and Aldencamp (1996) found test-retest reliability coefficients of .33 (Part A) and .56 (Part B) for the children's TMT. These coefficients were derived from a sample of 59 typically developing children between the ages of four and twelve who were tested a total of three times with six month intervals between testing sessions.

Given the low reliabilities of the adult and children's versions of the TMT, as well as the frequent use of adult measures for children, The Comprehensive Trail Making Test (CTMT) (Reynolds, 2002) was designed to include children in the standardization and to off-set many of the deficiencies of the original TMT. The CTMT enhances the original trails measure by utilizing five trails instead of two and by providing a nationally normed sample that includes children down to the age of 11. The five trails of the CTMT increase at various levels of difficulty to measure resistance to distraction, inhibition, task switching, and cognitive flexibility (Reynolds, 2002). Trail 1 of the CTMT is analogous to the previously described Trails A of the TMT where the examinee must draw a consecutive line through numbered circles on a page. The CTMT Trail 5 is similar to Trails B of the original TMT. For Trails B the task difficulty increases as the examinee must now switch between drawing from a letter to a number and then returning to a letter in the appropriate sequence (Lezak, 1995). For example, a correct line would start at 1, and then proceed to A, then 2, then B and so on. The additional trails added into the CTMT allows for increased specificity to help determine particular areas of deficit.

According to Reynolds (2002), the CTMT is specifically useful for detecting "frontal lobe deficits, problems with psychomotor speed, visual search and sequencing, and attention; and impairments in set-shifting..." (p. 5).

Despite the benefits of using the CTMT in assessing executive functioning, there have been relatively few studies using this measure after a childhood traumatic brain injury. Armstrong, Allen, Donohue, and Mayfield (in press) assessed 60 children and adolescents to examine the sensitivity of the CTMT. The sample included 30 children who had sustained a traumatic brain injury and 30 healthy controls matched on age, gender, ethnicity, and geographic region. The age range included 11- to 19-year-olds with the mean age of both groups being 15.0 years (SD = 2.3 years). Results indicated that the TBI group performed approximately 2 standard deviations below the comparison group on all five trails. The Composite Index for the TBI group was also 2 standard deviations below with significance noted at $p < .001$. Given the small sample size, factor analysis of the CTMT was not possible in this study. Instead the pattern of correlations between the trails of the TBI and control group samples was examined. A general pattern was noted with the TBI sample demonstrating higher correlations than the control group. All correlations were significant between the groups with the exception of the correlation between Trail 1 and 4 for the control sample. The largest differences were evident between the TBI and control group for correlations between the CTMT Trails 1 and 4, and between Trails 3 and 5, with the TBI group demonstrating higher correlations in both cases. The authors conclude that the significant correlations reflect the severity of impairment between groups.

Receiver operating characteristic analyses were also used to examine the sensitivity and specificity of each trail and the Composite Index. Results of this analysis demonstrated that all of the CTMT scores provided a significant increase in classification accuracy over chance ($p < .0001$) between the TBI and control groups. Good predictive discrimination was also noted among individuals with and without a TBI. Armstrong, Allen, Donohue, and Mayfield (in press) conclude that the CTMT maintains strong criterion validity and sensitivity when used to assess older children and adolescents who have experienced a TBI. The authors note that additional research is needed to validate these results with a larger sample size.

Purpose of the Study

The purpose of the current study was to confirm and expand upon the Armstrong, Allen, Donohue, and Mayfield (in press) research. Initial results from this study indicated that the CTMT was valid and sensitive for measuring the executive functioning skills in children and adolescents who have experienced a traumatic brain injury in contrast to typical developing individuals. The authors also noted that due to the small sample size a factor analysis could not be completed. In the standardization sample of the CTMT, a factor analysis identified two primary factors. The first factor included Trails 1 through 3 and was termed "Simple Sequencing." The second factor was comprised of Trails 4 and 5 and entitled "Complex Sequencing" (Reynolds, 2002). Armstrong, Allen, Donohue, and

Mayfield (in press) suggested that their preliminary findings warranted further examination of the CTMT factor structure within clinical populations.

The current study examined whether there was a significant difference between a TBI group and a control group on the CTMT Composite Index score. Supplementary investigation considered the differences between the clinical and control groups on each individual trail of the CTMT, as well as various groupings of trails. The current study replicated the Armstrong, Allen, Donohue, and Mayfield (in press) research with a larger sample size to confirm or refute the results. Additionally, the current study examined whether a similar two factor model, as evidenced in the standardization sample of the CTMT, was also present when using a TBI sample. This research added to the current understanding and knowledge base related to children's executive functioning skills post-injury. The results provide assistance to those practitioners and educators who work with this population in designing appropriate intervention plans to include individualized accommodations and modifications.

Assumptions

The demographic information for the clinical group that was obtained through the medical records of the children who had sustained a TBI was assumed to be correct. The assessments completed by trained practitioners were understood to be administered in the standardized manner and to be a truthful reflection of the children's functioning abilities.

Additionally, the data that was entered into the database by other individuals than the present researcher and not verified through the validity check were assumed to be entered accurately.

Limitations

Limitations of the current study included the lack of random selection of the clinical sample. Due to the fact that the TBI group had been patients from a hospital setting it is possible that results are unique to this sample and not generalizable to a larger TBI population. Additionally, given that the children were selected from a specialty care facility the severity of their injuries were likely more extensive than those presenting with mild head injuries. Research indicates that mild traumatic brain injuries comprise 90% of those who sustain an injury yet few of these seek medical assistance (Kraus, 1995). Given this knowledge, it is possible that the results may not be generalizable to the TBI population as a whole, but limited to those who have sustained a moderate to severe head injury. Another potential limitation is due to the age range of the standardization sample of the CTMT, which includes participants down to age 11. Given this constraint, the mean age range of the current clinical sample will only be applicable to older children and adolescents who have experienced a TBI.

Summary

Executive functioning skills are imperative for accomplishing tasks which require planning, organization, self-monitoring, and cognitive flexibility. All too often, those children and adolescents who sustain a TBI experience long-term deficits in their executive functioning skills. The immense impact these deficits may have on academic and behavioral functioning warrants research utilizing sensitive assessment techniques, which will drive the development of appropriate interventions. The current study expanded upon the existing knowledge base by comparing the executive functioning skills of children who have sustained a TBI to those with no injury to determine if significant differences exist between groups. Enhancing an earlier study with a larger TBI population potentially allowed for greater generalizability to other populations. Additional analyses were conducted to confirm the findings of the two-factor model comprised of Trails 1-3 (i.e., Factor One-Simple Sequencing) and Trails 4-5 (i.e., Factor Two-Complex Sequencing) reported in the CTMT standardization sample to determine if a similar structure was also present in a group of TBI participants. This study examined the hypothesis of whether the CTMT proved to be a valid and sensitive measure in evaluating and discriminating between clinical and non-injured populations. Additional research in this area added to the wealth of knowledge available to assist practitioners and educators who work with these children and adolescents as they acclimate to daily living post-injury.

CHAPTER II

LITERATURE REVIEW

Attempting to define executive functioning is a difficult task. The literature in related fields provides ubiquitous descriptions and classifications of related skills; however, a unified consensus of what encompasses executive functioning is lacking. Historically, executive functioning was conceptualized as a unitary concept based primarily in the frontal lobes (Anderson, 2002). While the involvement of the frontal lobes is fundamental, more recent knowledge indicates that executive functions are expressed through the interaction of multiple frontal-subcortical circuits connecting various regions of the brain (Fischer & Daley, 2007; Kolb & Whishaw, 2003; Lezak, 1995). This chapter will review the neurological substrates of executive processes and the theoretical models defining executive functioning. Secondly, the interaction of age and developmental trajectories on the expression of executive functions will be discussed. Thirdly, an overview of the assessment of executive functioning will be presented along with a review of the comprehensive and stand-alone batteries designed to measure executive control. Relevant research related to executive functioning and Traumatic Brain Injury (TBI) will also be examined and summarized. Lastly, specific measures designed to assess executive skills will be reviewed in regards to their applicability with individuals who have sustained a TBI.

Neurological Substrates of Executive Functioning

An understanding of executive functioning begins with knowledge of the underlying substrates and integrated circuitry involved in higher order cognitive processes. From a historical perspective, executive functioning was equivalent to frontal lobe involvement. Reynolds (2007) stated that the frontal lobes were once thought to be the exclusive domain for executive functioning tasks. However, the frontal lobes are now better understood to be the management system for prominent functions such as self-regulatory and generative behaviors, metacognitive control, and working memory (Reynolds).

Goldberg describes the frontal lobes as the part of the brain that "defines your identity, that encapsulates your drives, your ambitions, your personality, your essence" (2001, p. 1). The frontal lobes encompass all of the tissue anterior to the central sulcus comprising 29% of the total cortex (Goldberg, 2001). The frontal lobes are comprised of three distinct regions, which include the motor cortex, premotor, and prefrontal cortex (Carlson, 2004). The three major divisions differ from a functional perspective although each are involved in some respect with behavioral output (Lezak, 1995). The most posterior region, the primary motor cortex, is found in the first two ridges anterior to the central sulcus. This area mediates movement through connections with the cerebellum, the basal ganglia, and the motor areas of the thalamus (Lezak). In order to modulate these movements, the primary motor cortex utilizes two supporting pathways. One is the ventral-medial pathway which is primarily responsible for gross motor movements. The second pathway is the lateral motor system which controls fine-motor movements (Hale & Fiorello, 2004).

The premotor cortex is located just anterior to the primary motor cortex. This area has been associated with the ability to integrate motor skills during previously learned, routine sequences (Lezak, 1995). The premotor cortex can be subdivided into the supplementary motor cortex, frontal eye field, and supplementary eye field (Kolb & Whishaw, 2003). As previously described in relation to the primary motor cortex, the premotor cortex also integrates input from supplementary areas. Projections from the premotor cortex extend to other motor structures, such as the basal ganglia and the red nucleus, in order to coordinate the body's gross and fine motor movement (Kolb & Whishaw). The supplementary motor area prepares the body for action at a preconscious level (Kolb & Whishaw). Lesions within the premotor cortex do not cause an inability for motor activity; rather, it results in a disruption of the organization of the behavior. An individual with damage to the premotor cortex will likely demonstrate uncoordinated movements, a lack of continguity in motor sequences, and a deficit in limb strength (Lezak). While a further elaboration of the neuroanatomy of the primary motor and premotor cortices is outside of the scope of this review, it is important to understand the interaction of these two influential regions. The primary motor cortex provides the ability to accomplish a particular movement while the premotor cortex decides which movement will be executed (Kolb & Whishaw).

The final portion of the frontal lobes is the prefrontal cortex. The prefrontal cortex is considered the organizer or controller of the brain in regard to behaviors associated with executive functions. Goldberg (2001) analogized the prefrontal cortex to a conductor in an orchestra or a general in the army. The prefrontal cortex compiles all the information needed in the formation of goals and then integrates the necessary cognitive skills to carry out that plan (Goldberg). Goldberg explains that without the active involvement of the prefrontal cortex, an individual is left with a "head without a czar inside" (2001, p. 23). The active engagement of the prefrontal cortex depends on effective communication with the various components of the brain through complex circuitry. The networked pattern of the frontal lobes to the rest of the brain provides the connectivity necessary to oversee, integrate, and coordinate complex behaviors. The prefrontal cortex is the site where information from the limbic system, related to the internal state of the individual, and the pathways communicating information from external stimuli converge (Lezak, 1995). Thus all information, whether it is internal or external, past experience or present, conscious or unconscious, enters the prefrontal cortex and is integrated for use (Lezak). This integrative role of the prefrontal cortex demonstrates Goldberg's analogy of the relationship of the prefrontal cortex to the brain as being parallel to a conductor for an orchestra. The "conductor" of the brain coordinates multiple types of input and is able to integrate the cacophony of information into a meaningful plan of action. To convey an accurate understanding of the frontal lobes with the interrelated regions of the brain, the remainder of this neuroanatomical review will focus on the cortical and subcortical circuitry of the frontal and prefrontal systems.

The underlying neurophysiology of executive functions is comprised of multiple inter-related, interdependent subsystems. These integrated circuits function concurrently to provide a reciprocal supervisory control system (Anderson, 2002). Within the frontal and pre-frontal areas there are several subcortical circuits that comprise the aforementioned reciprocal control system to produce the complex behaviors related to executive functions. The frontal subcortical circuitry includes the skelelomotor, oculomotor, inferior-temporal/ posterior parietal, anterior cingulate, ventromedial orbitofrontal, lateral orbitofrontal, and the dorsolateral prefrontal circuit (Miller, 2007). These circuits are often referred to as "loops" due to the reciprocal exchange of information across systems (Hale & Fiorello, 2004). The skeletomotor circuit is involved in regulating both fine and gross motor movements through output from the premotor, supplementary motor, and primary motor areas (Miller). The oculomotor circuit assists in integrating information obtained from the frontal eye fields, prefrontal, and parietal cortex (Hale & Fiorello). Deficits in the skelemotor circuit or the oculomotor circuit would be evident in tasks that required motor control or visual scanning and attention. The inferior temporal/ posterior parietal circuit has yet to be clearly defined; however, it is hypothesized to be involved in working memory functioning within the frontal lobes (Litchner & Cummings, 2001).

The last primary circuits to be described are intricately involved in the process and output of the characteristic behaviors associated with executive functioning. The dorsolateral prefrontal circuit is influential in regulating multiple processes which include utilizing organizational strategies, planning desired behaviors, and sustaining attention in order to complete a task. This complex circuitry is also involved with cognitive flexibility and the ability shift set during a task (Miller, 2007). Hale and Fiorello (2004) state that deficits in the dorsolateral prefrontal circuit lead to the "classic signs of attention deficits" (p. 64). These deficits are evident through behaviors such as inattention, poor problem solving, disorganization, and difficulties monitoring and evaluating one's own motor activities.

The orbitofrontal circuit is also actively involved during executive functioning tasks. Orbitofrontal circuitry is activated during the decision making process with the integration of emotional reactions and context-specific variables (Miller, 2007). An individual with deficits in the orbitofrontal circuit may lack the ability to assess a social situation in order to adjust or inhibit an inappropriate behavioral response. For example, those with orbitofrontal syndrome may engage in shoplifting, reckless driving, or sexually inappropriate behaviors without any concern for rules or legal prohibitions (Goldberg, 2001). The third primary circuit involved in executive functioning is the anterior cingulate circuit. This circuitry is involved in the initiation of motor movement, as well as the motivation necessary to complete a task (Miller). Hale and Fiorello (2004) note that deficits in the anterior cingulate circuit may be evident due to slow completion time on tasks, lack of persistence, limited creative thought, or difficulties in self-monitoring performance. While all of these circuits are essential in the demonstration of executive functions, it is imperative to note that it is the interaction of these circuits and additional sub-cortical circuits that result in efficient executive control (Hale & Fiorello).

The frontal lobes and the connecting pathways are particularly vulnerable to injury. An initial account of frontal lobe damage can be understood through the case history of Phineas Gage. Gage was struck by a tamping rod which impaled his left cheekbone and continued up through his frontal lobes damaging the orbitofrontal circuitry (Harlow, 1848). Gage was able to recover from the accident; however, his acquaintances reported significant personality and behavioral changes due to the trauma. This once personable, amiable man was now impulsive, disrespectful to authority figures, and often lacked social awareness. As can be seen from this historical account, damage to the frontal lobes significantly impact an individual's functioning, even when external, physical abnormalities do not exist. Goldberg (2001) states that the frontal lobes are more vulnerable to injury than any other area of the brain. When there is damage to the frontal lobes wide "ripple effects" are seen throughout the brain (Goldberg). In the same way, due to the reciprocal nature of the pathways, damage to other portions of the brain can interfere with efficient frontal lobe functioning.

Definition of Executive Functioning

The study of executive functioning was propelled by the pioneering work of Alexander R. Luria. Through his experience with brain injured survivors of World War II Luria understood the importance of connecting the brain's processes with observable behavior (Goldberg, 2001). Luria believed that to have a deeper understanding of the psychology of the brain, one must study both the brain and the interaction of the systems within the brain (Stuss & Benson, 1986). Luria proposed that the frontal lobes were primarily responsible for behaviors such as self-monitoring, planning, and regulating one's actions, all of which are skills strongly associated with executive functioning. (Hughes & Graham, 2002).

Although the nature of the relationship between the frontal lobes and executive functions continues to be debated, Luria's influential work has become a foundational component to later theoretical definitions. Luria (1973) believed in the hierarchical organization of the brain and proposed a model based on three primary tenets. The first of these tenets is that the brain is organized hierarchically from basic to complex regions and focuses on how information is being processed and the subsequent behavior initiated. According to Luria, afferent information is processed through the subcortical regions and then on to the primary cortical zones. The information is then hierarchically processed through the secondary association areas and then the tertiary cortex. All information, regardless of the sense modality, is processed within the tertiary zone where understanding takes place or a plan of action is conceived (Hale & Fiorello, 2004). The second major tenet states that the cortical areas lessen in their specificity from simple processing to higher order functions based on integrated circuitry. For example, the primary cortex works predominately with one sensory modality while the tertiary cortex can concentrate on multiple modalities (Hale & Fiorello). The third tenet of Luria's model asserts that the brain increases in lateralization of function as the information ascends the hierarchy. This results in the hemispheres organizing and representing knowledge in different ways (Hale & Fiorello).

Luria posited that this hierarchical organization of the brain was evidenced through three functional units. The first functional unit includes the reticular system and is primarily responsible for the sleep/wake cycle and regulating tone (Hale & Fiorello, 2004). The second functional unit encompasses the posterior occipital, parietal, and temporal regions of the brain. These regions are responsible for taking in information, as well as analyzing and storing input. The third functional unit houses the anterior portion of the cortex and the frontal lobes. This third unit was considered by Luria (1973) to be the superstructure of the brain, functioning in a governing role for almost every area of cortical functioning. While each unit builds on the previous, all areas work together to perform cognitive activities. Due to this concerted interplay, Luria stated that damage to one area is likely to disrupt the pattern of functioning in other areas.

The complex, reciprocal systems involved in executive control make developing a cohesive definition of executive functioning challenging. While it is widely accepted that executive functioning can no longer be conceptualized as a single process, the fields of cognitive, developmental, and neuropsychology remain polarized in determining a cohesive definition (Fisher & Daley, 2007). In response to this lack of consensus, Baddeley asks the question of whether it is better to describe executive control as "a unified system with multiple functions, or simply as an agglomeration of independent though interacting control processes" (1996, p. 5). To allow for the inclusion of these multiple functions it may be best to conceptualize executive functioning as an umbrella term that encapsulates a complex set of processes related to "independent, purposive, self-serving behavior" (Lezak, 1995, p. 42). Lezak describes executive functioning as being comprised of four components which include volition, planning, purposeful behavior, and effective performance. Norman and Shallice (1980) define executive functions as necessary in situations that involve planning and decision making, changing in response to error, initiating novel responses to situations, responding to unforeseen situations, and inhibiting or overcoming an ingrained, habitual response. From this perspective, executive functioning is not primarily used during well-learned, routine behaviors. Rather, these higher order cognitive skills are specifically activated in novel or unfamiliar situations where prior routines do not exist (Anderson, 1998).

Reynolds (2007) discusses executive functioning as involving decision-making, planning, inhibition, and sequencing, as well as the development and implementation of motor output. He continues by differentiating between executive functions and knowledge. Knowledge encompasses the retention of specific facts whereas executive functioning utilizes that knowledge to make decisions and adapt to novel situations.

Knowledge is passive maintenance of declarative information versus the active, generative nature of executive functioning (Reynolds). While specific definitions and conceptualizations vary, there appears to be a generalized consensus that executive functions are comprised of multiple distinct, yet interrelated abilities. This construct of executive functioning facilitates supervisory, intentional, self-regulatory, goal-directed and problem solving behaviors (Gioia, Isquith, Kenworthy, & Barton, 2002).

Theoretical Models of Executive Functioning

Given the lack of definitional consensus and the wide range of cognitive abilities subsumed in the term 'executive functioning,' multiple models have been developed to describe the interrelated processes within the executive system (Busch, McBride, Curtiss, & Vanderploeg, 2005). These models can be categorized based on the way they are conceptualized. Zelazo, Muller, Frye, and Marcovitch (2003) discuss the delineation of executive functioning models. The first approach conceptualizes executive functioning as a "higher order cognitive mechanism" (Zelazo et al., p. 1). This method examines executive functioning based on demonstrated abilities such as inhibition, working memory, or planning. However, this type of model limits the ability to answer questions related to how executive functions are achieved and the processes involved in their manifestation. The second format for examining executive functioning involves utilizing extensive neuropsychological batteries. The results of these assessments are then factor analyzed in an effort to determine the foundational elements of executive functions (Zelazo et al.). The factor analysis typically leads to three or four factors that are labeled and described as separate dimensions of executive functioning. This methodology may be misleading in that the labels for each factor are arbitrary and the same assessment may be clustered in different ways depending on the categorization of the factors. Ylvisaker and DeBonis (2000) expound on this weakness by stating that factor analytic methods for determining executive functions are a poor statistical tool because the outcome is determined by the researcher's choice of assessment measures. Oftentimes, specific subcomponents of executive functioning do not emerge as independent factors because they are not significant facets of the chosen tests (Ylvisaker & DeBonis).

The third approach conceptualizes executive functions as an operative, functional construct that attempts to reference the processes involved in goal-directed, problem-solving behavior (Zelazo et al., 2003). Taken from a similar perspective as Luria's functional units, this method allows for hypotheses to be made regarding the role of cognitive processes in the different areas subsumed in executive functions. For example, a problem-solving task would involve multiple steps such as defining the problem, deciding on a plan to address the problem, executing that plan, and then evaluating the outcome in order to determine the next step. This way of conceptualizing executive functioning avoids aggregating abilities into one unified function and attempts to clarify how the various characteristics of executive functioning operate concurrently (Zelazo et al.). Each method of conceptualizing executive functioning has its own strengths and weaknesses. The following review will highlight various executive functioning models from each of the three approaches described above.

Stuss and Benson (1986) take the first approach to conceptualizing executive functioning by basing their model on the demonstrated abilities theoretically comprising executive functions. According to Stuss and Benson, executive functioning includes the components of drive, sequencing, and control. In this model drive was defined as the processes involved in the will and the motivation necessary to accomplish tasks. Difficulties with drive would be evident through behaviors such as motoric slowing or apathy, or an inability to sustain a behavior in order to accomplish a pre-determined goal (Stuss & Benson). The opposite of behavioral apathy can also be indicative of frontal lobe abnormality where an individual exhibits excessive drive and an inability to inhibit actions.

The second component of Stuss and Benson's model is termed sequencing. Sequencing is defined as the capability to order and categorize information from incoming stimuli. This information is then organized into related sets and integrated with other information to form the appropriate behavioral response (Stuss & Benson). Deficits in sequencing are demonstrated when lesions or injury occur in the dorsolateral prefrontal cortex, which results in an inability to perform the sequential steps necessary to generate behavioral control. The functions of drive appear to be primarily dependent on medial frontal structures, while the abilities of sequencing rely on the lateral frontal functions (Stuss & Benson). These two units of mental activity interact concomitantly with each other, and the posterior regions, to produce mental and behavioral control.

According to Stuss and Benson's model (1986), the executive component of control acts as a monitor between drive and sequencing. The neuroanatomical location for the concept of control is in the prefrontal cortex. When a new activity is being learned, the prefrontal cortex becomes active to know how to respond to these non-routine, novel situations (Stuss & Benson). The behavioral characteristics of control include anticipation, goal selection, pre-planning activities, and the ability to monitor one's own behavior, which are all considered separate components of executive functions. See Figure 1 for Stuss and Benson's hierarchical model of executive functioning.

Stuss and Benson's model is similar to Baddeley's model of working memory. Baddeley (1986) proposed a tripartite model which utilizes the central executive as the "supervisor" between two slave systems. The subordinate systems include the phonological loop and the visual-spatial sketchpad. The phonological loop integrates language functioning and the visual-spatial sketchpad is primarily responsible for interpreting spatial material (Baddeley). This model demonstrates the interaction of subsystems to handle lower level tasks, while the essential processor and integrator remains within the central executive. This conceptualization of executive functioning is similar to a model put forth by Norman and Shallice (1980) who propose executive functioning as a "supervisory system."

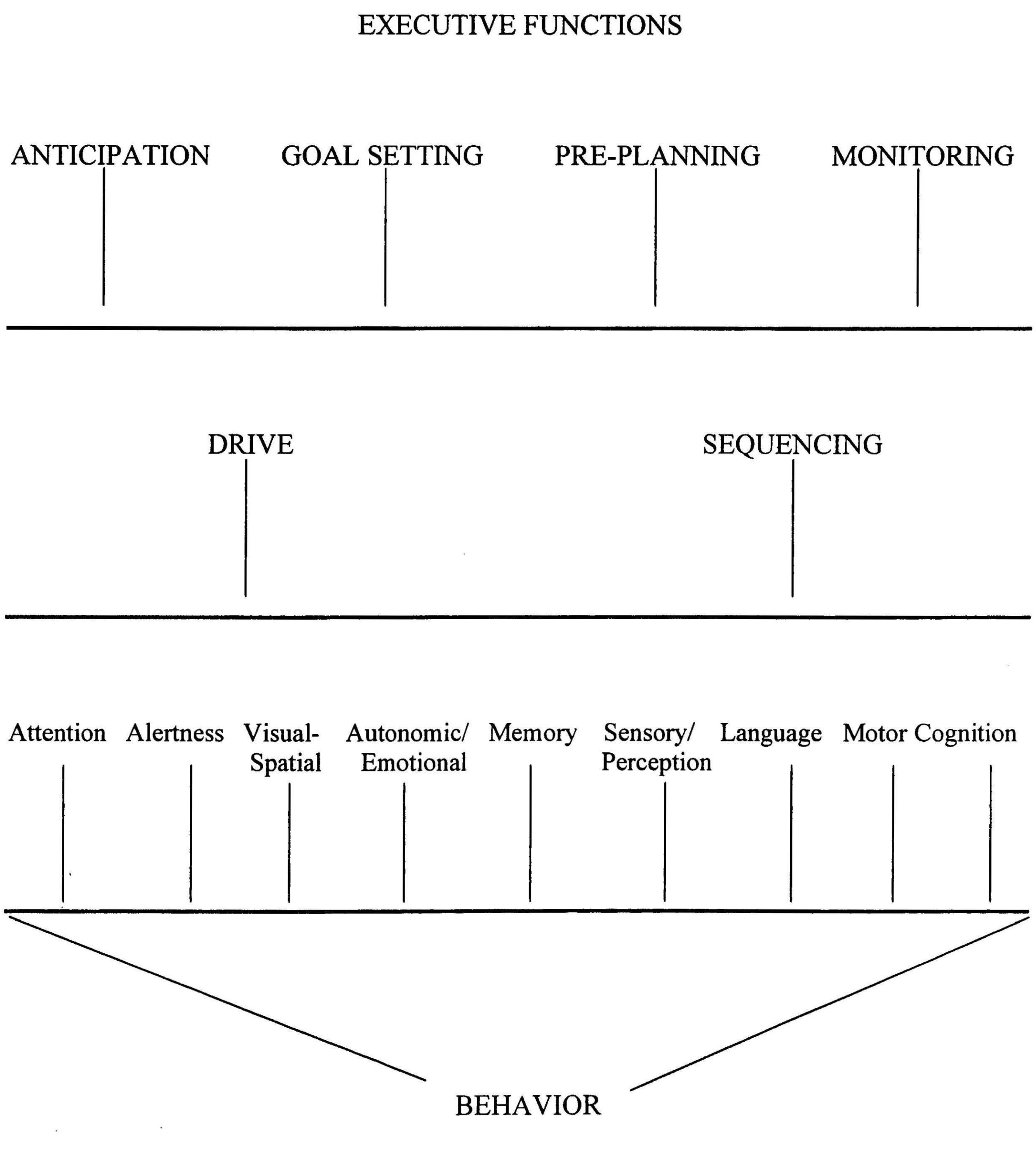

Figure 1. Stuss and Benson's Model of Executive Functions (1986).

Shallice (1982) expands on this conceptualization by adding a more detailed model with four distinct components of executive functioning. These discrete aspects of executive functioning in the model are termed cognitive units, schemas, contention scheduling, and the supervisory attentional system. Cognitive units are defined as specific neuroanatomical systems related to a particular task such as motor functions or visual spatial abilities (Stuss & Benson, 1986). Within this model, schemas are defined as the integrative component for organizing the specific cognitive unit functions. Schemas are conceptualized hierarchically and primarily deal with routine tasks (Shallice).

The next component of the model includes the area of contention scheduling. This factor selects the appropriate schema for the completion of a desired task and integrates the necessary behavioral and sensory demands to accomplish the task (Shallice, 1982). An example of contention scheduling would be a last minute decision to stop by the donut shop on the way to work. The executive component allows for the modification in the initial goal (i.e., getting to work) and integrates the behavior necessary to stop by the bakery. The last component of Shallice's model includes the supervisory attentional system. The supervisory attentional system is theorized to handle non-routine tasks where contention scheduling has failed and a novel behavioral response is required for that situation (Shallice). If the donut-loving individual stops quickly in the parking lot and is rear-ended by another car, the supervisory attentional system would now take over so that individual can respond appropriately to this non-routine situation.

Factor analytic studies have also been used to better understand executive functions. Anderson (2002) examined the research on the developmental components in executive functioning derived from factor analytic studies. Anderson compiled relevant research and proposed a model of executive functioning, which is shown in Figure 2. Anderson reported that similar factors were seen across multiple studies despite the use of differing test batteries and various age ranges. This model divides executive functioning into four discrete categories that operate concurrently. The four areas include attentional control, cognitive flexibility, goal setting, and information processing. Each realm processes input from multiple areas and together these four domains function as a control system (Anderson).

The attentional control factor includes the ability to selectively attend, inhibit responses, and sustain attention over an extended period of time. Attentional control also involves the ability to monitor and evaluate a plan of action until a desired goal is achieved. Deficits in attentional control would be seen through impulsivity, lack of self-control, and incomplete tasks (Anderson, 2002). The second factor is termed information processing and includes abilities such as fluency and efficiency in output. Information processing is often measured by the accuracy and time needed to complete a desired task (Anderson). Deficiencies in the information processing domain would be demonstrated through minimal output, extended time for completion, and delayed reaction times.

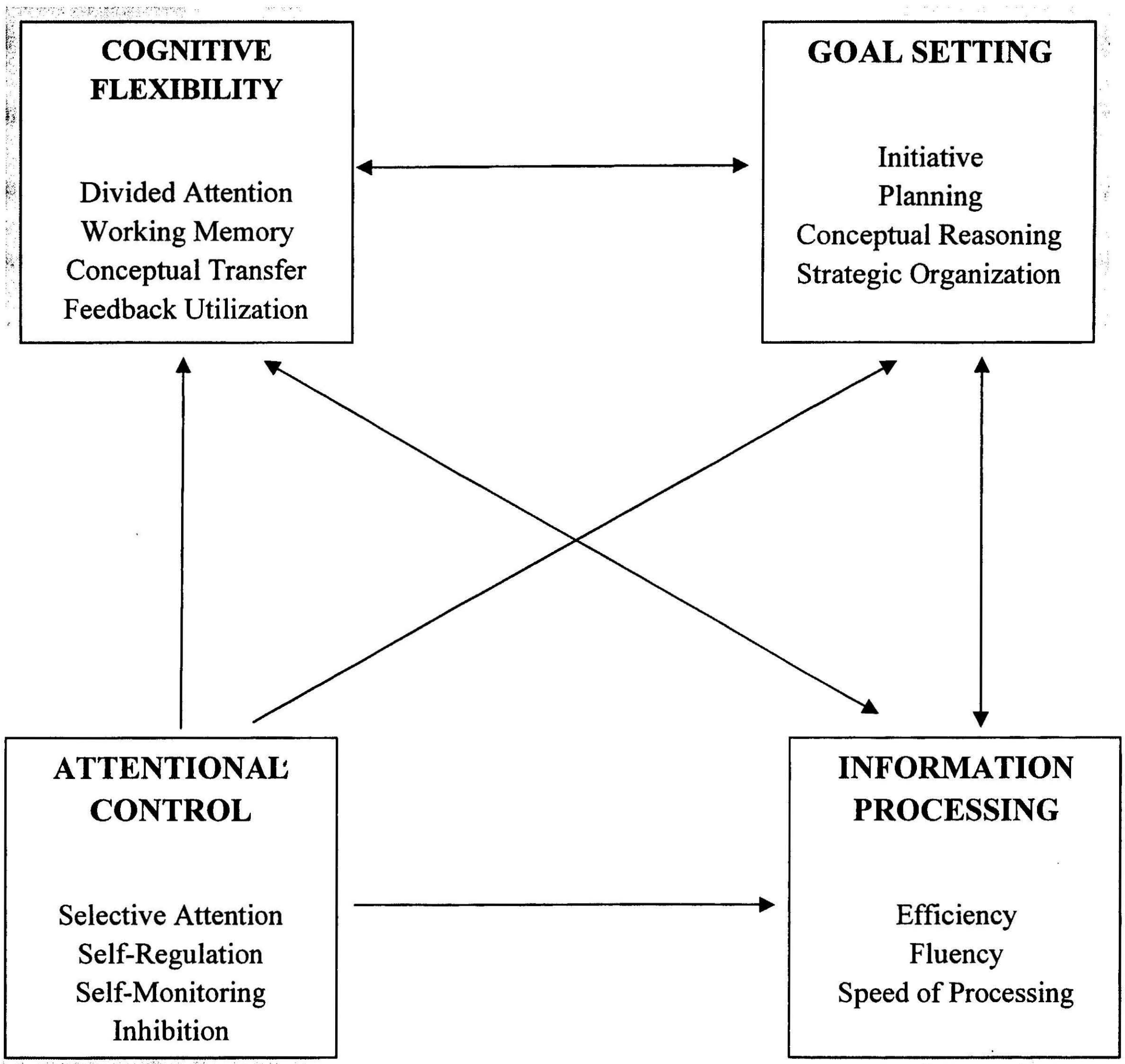

Figure 2. Anderson's developmental model of executive functioning (2002).

The third factor in Anderson's model of executive functioning is termed cognitive flexibility. This characteristic of executive functioning encompasses the ability to shift between cognitive sets, change desired responses, and process information from multiple sources concomitantly (Anderson, 2002). Deficits in cognitive flexibility are noted through the evidence of preservative behaviors, rigid routines, as well as difficulties adapting to changing demands. The final factor of Anderson's model addresses goal-setting behaviors. This domain incorporates the ability to plan actions in advance, approach novel tasks efficiently, and utilize existing knowledge to apply it to the current demand. Difficulties in this domain would be evident through poor planning abilities, deficits in conceptual reasoning, and disorganization. Of these four domains, attentional control functions with the greatest influence over the other domains; however, all are interdependent and operate in an interrelated manner to coordinate as an overall control system for the individual (Anderson).

Additional models of executive functioning have been proposed to account for the cognitive deficits demonstrated as the result of a traumatic brain injury. Busch, McBride, Curtiss, and Vanderploeg (2005) examined individuals at one-year post-injury to explore the subcomponents of executive functioning within this population. The 104 participants had all sustained a closed head injury and were active military duty personnel or military veterans. Various neuropsychological batteries were carefully chosen to attempt to encapsulate unique aspects of executive functioning. The results revealed a three factor model that accounted for 52.7% of the variance (Busch et al.). The first factor represents higher order cognitive functioning. This factor includes two subcomponents of cognitive flexibility, as measured by task-switching responses, and self-generative behavior, which was measured by various fluency tasks. Busch and colleagues suggest that the primary factor represents traditional neuropsychological measures of executive functioning reflecting abilities such as fluency, self-initiation, sustained on-task behaviors, and cognitive flexibility. Busch et al. hypothesized that the behavioral characteristics associated with mental control and initiation were mediated through activity in the dorsolateral prefrontal region.

The second factor represents mental control. Mental control was defined as the ability to sustain attention despite distractions and mental tasks. Tasks within this factor measured the individual's ability to repeat numbers backwards and change cognitive set (Busch et al., 2005). Results indicated that the third factor was comprised of errors in memory, perseverative responses, and inaccurate designs on visual spatial tasks. This memory error factor was also characterized by a lack of inhibition when stating incorrect information (Busch et al.).

As is evident from this overview no single model can accurately explain all aspects of executive functioning. Given the ubiquitous nature of executive functions, it remains a challenge to conceptualize or define the processes and behaviors associated with executive skills. Executive functions can be conceptualized based on the demonstrated abilities, through extensive neuropsychological testing and factor analysis, or by conceptualizing the construct through the processes involved in goal-directed, problem-solving behavior. Each approach to conceptualizing executive functions evidences its own strengths and weaknesses. Within each of these approaches, models of executive functioning have been highlighted in an attempt to describe the interactions of these abilities within the complex system of executive functioning.

Developmental Aspects of Executive Functioning

Behaviors such as poor reasoning abilities, lack of self-monitoring, and reduced working memory may all be associated with executive functioning deficits. However, when understood from a developmental context, those behaviors would not be considered significantly abnormal in a 3-year-old (Anderson, 2002). This example highlights the importance of understanding the developmental trajectories associated with executive functioning. An attempt to better understand developmental disorders and early psychopathologies has fueled research in childhood executive functioning (Blair, Zelazo, & Greenberg, 2005). However, the research advancements are yet again faced with the challenge of a lack of definitional congruence of executive functioning. This difficulty is then coupled with the rapid developmental changes taking place in a child's brain. Due to the rapid development of executive functions in early childhood, accurately studying these skills remains a constant challenge (Carlson, 2004). This difficulty is heightened given the fact that development is not linear and usually takes place in maturational spurts (Anderson). It was originally thought that executive functions did not emerge until the frontal lobes had matured into young adulthood. However, it is now understood that these higher-order processing skills are developing long before they are observable, functional, and therefore testable (Anderson). Developmental profiles vary depending on the skill examined and trajectories differ as the brain matures.

Multiple studies have examined the interaction between developmental processes in the manifestation of executive functioning abilities. Zelazo, Muller, Frye, and

Marcovitch (2002) studied the development of rule-based learning systems in 3- and 4-year-olds. Zelazo and colleagues discovered that the difficulties demonstrated by the young children on a card sorting task were not related to memory impairments, but were likely attributable to the conflict among the rules that were presented. On this task children were asked to sort a series of cards that varied on two dimensions of color and shape. Regardless of which dimension was directed as the first sort, 3- and 4-year-olds tended to perseverate by sorting based on the initial criteria. However, by 5-years-old children were able to successfully inhibit the salient feature and sort by another given criteria (Zelazo et al.). This perseverative tendency of young children has been interpreted as a failure to suppress an overlearned response (i.e., sorting by the initial characteristic) even though the children were able to verbally state what the new "rule" was for the second sort. This lack of cognitive flexibility decreases as the dorsolateral prefrontal cortex matures (Zelazo et al.).

The importance of assessing executive functioning from a developmental perspective was demonstrated by Espy, Kaufmann, Glisky, and McDiarmid (2001) who studied ninety-eight preschool children across five age groups (i.e., 30-, 36-, 42-, 48-, and 60-month age groups). Espy and colleagues utilized multiple neuropsychological measures that purportedly tap into various aspects of executive functioning. These measures assessed executive skills such as working memory, inhibition, cognitive flexibility, problem-solving and planning. An estimated level of intelligence was also factored in to the assessment battery. Results indicated that executive functioning improved across the 30- to 60-month age groups (Espy et al.). Specifically, age related improvements were noted on working memory and inhibition measures as fewer perseverative errors were made. Progress was also seen when examining problem-solving and planning abilities across the age groups. Espy and colleagues emphasize the importance of breaking down the age groups into six-month intervals due to the rapid changes that are taking place developmentally during this period. When examining reversal task performance, it appears that the developmental trajectory presents in a stair-stepped fashion, rather than gradually unfolding across the age range, as was evident in the other aspects of executive functioning. Performance on these measures of executive functioning was essentially independent of intellectual abilities. This suggests that executive functioning tasks are measuring skills that are distinct from intelligence, even in preschool children whose higher order cognitive abilities are not as discrete as in older children or adults (Espy et al.).

Diamond, Carlson, and Beck (2005) also examined executive functioning in young children. Diamond and colleagues specifically tested task switching abilities and inhibitory processes in 57 children age 2 ½, 3, and 3 ½ years-old. It is understood that young children have difficulty integrating characteristics of a single object as well as switching between salient features of a given stimuli. Diamond and colleagues utilized a card sorting task which displayed pictures of familiar objects in a primary color, to measure children's ability to sort based on one prominent attribute and then switch to sorting by a different criteria. It was evident that 3-year-olds are able to sort based on a given category (e.g., color); however, they have difficulty when asked to ignore the color and then sort by shape. Diamond and colleagues have termed this tendency for young children to continue to respond to a predetermined attribute as attentional inertia. Children around the age of 3-years-old have a propensity to get stuck on the "blueness or redness of a stimulus" and then "once they have focused their attention on one dimension, their attention gets stuck there" (Diamond et al., p. 691).

The use of the card sorting task demonstrated that the young children were significantly better at switching between color and shape (and between shape and color) as long as the color was in the background and not in the shape itself. For example, in the separated sorting condition, the object was presented in a primary color (e.g., red, blue, etc.) on a white background. The integrated condition differed in that it had pictures with the object (e.g., a truck or star) in one color with the background in another color. Age related differences were strongly evident across both conditions (Diamond et al., 2005). Approximately 15.8% of the 2 ½ year-olds could sort in the separated condition, but only 10.5% could switch between the background color and the object color to correctly sort given the parameters. The condition made a drastic difference at 3-years-old where three times as many children (37.5%) could sort when the dimensions were separated than when they were integrated (12.5%). At 3 ½ years old the difference equated to approximately 2 times as many children were able to sort correctly in the separated condition (64.3%) versus the integrated condition (35.7%). Diamond et al. concluded that success on the switching tasks demonstrated a clear age-related progression in the separated condition. The integrated condition showed significant developmental progress between the ages of 3-years-old and 3 ½ years-old. These results again validate the importance of factoring age and developmental factors when interpreting executive functioning measures.

The development of executive functioning was investigated in an older group of children by Brocki and Bohlin (2004) through a cross-sectional analysis of 92 children ranging in ages from 6- to 13-years-old. Several prominent neuropsychological measures were used to assess the differing characteristics of executive functioning. Inhibition and interference were measured through a computerized go/no-go task as well as a Stroop-like measure. A continuous performance task was utilized to assess vigilance and response inhibition. Verbal and non-verbal working memory were evidenced as salient factors of executive functioning when measured through a hand-movement task and a digit span task (Brocki & Bohlin). Verbal fluency was assessed using a task that required semantic fluency (i.e., generate as many animals as you can within one minute) and phonetic fluency (i.e., state as many words as you can that start with the letter S within one minute). Analysis of the assessment results indicated three primary factors: Disinhibition, Speed/Arousal, and Working Memory/Fluency (Brocki & Bohlin). The Disinhibition factor was comprised of the continuous performance test disinhibition and impulsivity factors and the go/no-go commission errors. The Speed/Arousal factor included the continuous performance test reaction time, go/no-go reaction time, and inattention errors on the continuous performance test and go/no-go task.

The third factor, Working Memory/Fluency, consisted of semantic and phonetic fluency, the hand movement task, the digit span task, and the Stroop-like task (Brocki & Bohlin, 2004). These three primary factors were analyzed to determine any significant age effects across the sample. On the Disinhibition dimension, substantial developmental changes were evident across the age range of 7.6- to 9.5-years-old and from 9.6- to 11.5-years-old. The Speed/Arousal factor also showed significant age trends within the first group of 6 to 7.5 year-olds and the second group consisting of 7.6- to 9.5-year-olds. The third factor, Working Memory/Fluency, demonstrated two developmental shifts around the age of 8-years-old and 12-years-old (See Figure 3 for the developmental trajectories of the three factors). The results of this investigation demonstrated that the developmental trajectories depended on the aspect of executive function being examined. The Speed/Arousal dimension appeared to be the first characteristic of executive functioning to reach maturity. The Disinhibition factor revealed maturity around the age 10, while Working Memory/Fluency skills continued to develop into adolescence (Brocki & Bohlin).

Executive functions in relation to attentional control appear to experience a strong developmental shift during infancy and early childhood (Anderson, 2002). However, monitoring and self-regulatory processes do not appear until around the age of 9- to 10-years-old. There appears to be a brief regression in self-regulatory behavior between the ages of 11- and 13-years-old that leads to an increase in impulsivity. Anderson postulates that this regression may be due to changes within a developmental phase where competing demands are in conflict and executive control is needed yet not developed.

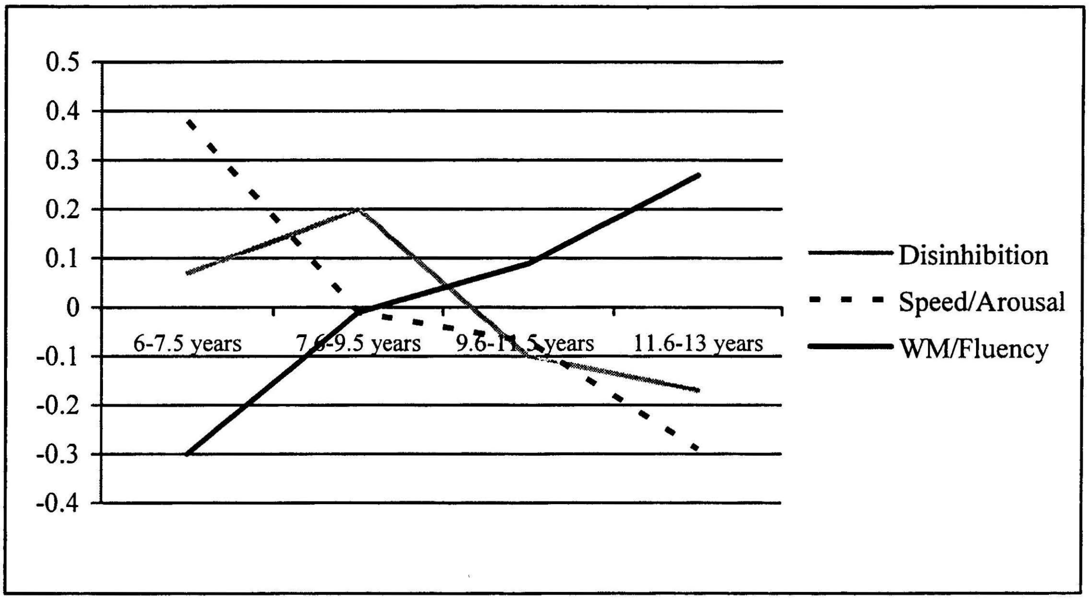

Figure 3. Brocki and Bohlin's function of age on factors of disinhibition, speed/arousal, and working memory/fluency.

The development of executive functions continues as the frontal lobes mature into young adulthood. Evidence of this development is seen as a fully, integrative collaborative system. Romine and Reynolds (2005) conducted a meta-analysis of multiple studies to examine executive functioning developmental trajectories from ages 5- to 22-years-old. Effect sizes were calculated across eight studies to determine age-related changes in performance in the areas of planning, verbal fluency, design fluency, preserveration, and set maintenance. Results indicated that the largest period of development occurred across the age span of 5- to 8-years-old for the domains of planning, fluency, and inhibition (Romine & Reynolds). Increases were demonstrated across all executive domains from 8- to 11-years-old. A small increase in inhibitory responses was evident from 11- to 14-years-old; however, no age-related increases were noted in this area after this time period. The executive skills of planning and verbal fluency demonstrated the strongest increase in the oldest age span of 17- to 22-years-old (Romine & Reynolds). The results of this study demonstrate the importance of interpreting data using age-corrective normative data. When executive functioning is measured across developmental periods, the peak performance depends on how each specific skill is assessed.

Evidence from electroencephalogram (EEG) studies also provides information on the developmental progression of the frontal lobes and the resultant executive control. It is hypothesized that the greater amount of "power," or electrical energy measured by the EEG, reflects brain reorganization relating to the new capacities that emerge at several ages (Fischer & Daley, 2007). Using quantitative EEG (qEEG) measurements, Hudspeth and Pribram (1990) found that the brain demonstrated five distinct growth cycles of spurts and plateaus within the first 21 years of life. Four primary brain regions were recorded with the qEEG, which included the parieto-occipital, temporo-temporal, centro-central, and fronto-temporal regions (Hudspeth & Pribram). During the first decade of life, maturation was noted across all four areas. When specifically examining the frontal regions, rapid growth was evidenced between the ages of birth to five years old, which is consistent with the increase in attentional control discussed previously. Specific subcomponents of executive functioning such as information processing, cognitive flexibility, and goal setting, experience significant development shifts between the ages of 7- and 9-years-old (Anderson, 2002). From early adolescence, the temporal, central, and frontal regions demonstrate different onsets and offsets of rapid change. Synchrony of maturation was noted in the parieto-occipital, temporal, and central regions from ages of 13- to 17-years-old although peaks of growth were notably separated by approximately 1 year intervals (Hudspeth & Pribram). The fifth stage of growth, which included individuals between the ages of 18- to 21-years-old, was primarily in the frontal regions indicating brain maturation from the posterior to the frontal areas of the brain (Hudspeth & Pribram). These results support the study reported earlier (i.e., Romine & Reynolds, 2005) that the frontal lobes continue development into young adulthood.

As is apparent, the development of executive functions is not a unified process. Multiple studies have been reviewed that demonstrate the interaction between developmental processes in the manifestation of executive functioning (Blair, Zelazo, & Greenberg, 2005; Brocki & Bohlin, 2004; Diamond et al., 2005; Zelazo et al., 2002). Young children evidence executive functioning deficits by a lack of cognitive flexibility or preserverative tendencies. Task-switching abilities also show a developmental change where the younger participants were unable to switch between given sorting conditions (Diamond et al.). Evidence from qEEG measurements indicates that there are several growth periods across specific regions of the brain. Increases in the amount or the strength of the frontal lobe connections demonstrate significant developmental maturation within the first five years of life and continue through the age of 21 (Hudspeth & Pribram, 1990). Despite the differing developmental trajectories of executive functioning abilities, an understanding of the neurological development is imperative when attempting to assess these burgeoning abilities.

Assessment of Executive Functioning

Given the lack of definitional congruence and complexity of executive functions, multiple measurement issues arise. The complexity of tasks designed to measure executive functions, often represent the combined effect of multiple underlying processes (Hughes & Graham, 2002). Constructs within executive functioning, such as working memory and attention, overlap and each construct contributes to outcome measures of executive functioning (Romine & Reynolds, 2005). For example, a task that purportedly measures inhibition also likely involves the executive processes of divided attention and strategic planning. The integrative nature of frontal lobe functioning makes it difficult to parcel out the specific cognitive functions being utilized in each type of task. This interrelatedness of executive functions leaves measurement practices vulnerable to task impurity (Hughes & Graham). Romine and Reynolds state that it may be "impossible to obtain a pure test of frontal functions because an element of theoretical constraint of frontal functions is that they involve simultaneous management of a variety of cognitive functions" (pp. 198-199).

An additional issue arises due to the fact that there is low congruence between focal neuroanatomic locations and specific behaviors. Few behaviors are solely the result of one area of the brain. Rather, multiple subcomponents and interconnected circuitry result in the observable behavior. Other areas of the brain are simultaneously interacting during executive control tasks. For example, the anterior cingulate cortex, as well as the cerebellum, has been noted to be activated during tasks that involve the prefrontal cortex (Romine & Reynolds, 2005). This significantly affects the measurement of executive functioning because a deficit in one processing area may lead to multiple behaviors. The opposite can also be true in that one behavior may be the result of multiple underlying impairments. Hughes and Graham (2002) state that this incongruity results in no "operational definition for executive functions and hence no universally accepted prototypical 'executive function task' that is failed by all individuals with dysexecutive syndrome" (p. 132). Given that the prefrontal cortex does not act in isolation, it is very challenging to identify which regions of the brain contribute to outcomes on specific executive functioning measures (Romine & Reynolds). Assessment of executive functioning may also be hindered due to the standardized nature of the testing situation. The examiner guides the assessment process and often acts as the "conductor" during the subtests. While the standardized procedures are essential, it is possible that the manner in which executive control is measured may mask the extent of the deficits (Slomine, Gerring, Grados, Vasa, Brady, Christensen, et al., 2002).

Despite these assessment difficulties, Hughes and Graham (2002) offer several possible advantages to utilizing multi-componential models designed to emphasize the fractionated nature of executive control. When assessing executive control through this framework, specific task demands can be analyzed during an assessment to coincide with components of a model (Hughes & Graham). However, fractionated models can also create more difficulties due to the complex nature of executive behaviors. For example, in order to complete a complex task a plan often needs to be generated before it can be acted upon. However, an individual lacking executive control may not be able to plan appropriately and therefore not successfully complete the task. The difficulty therein lies in determining whether the lack of output was the result of poor planning or lack of follow-through. Since multiple sub-processes need to be activated it is often difficult to parcel out which "fractioned" area of executive functioning caused the resulting task incompletion (Hughes & Graham).

Assessment of Executive Functioning in Children

Assessing executive control in children adds another challenge due to the intricate interaction of age and development. Executive functions are theorized to change with maturation and may take different forms at different ages (Archibald & Kerns, 1999). Hence, it is important that childhood assessments of executive functions need to be well-researched to ensure that the developmental aspects of executive control are truly being measured (Archibald & Kerns). Brocki and Bohlin (2004) discuss how executive functioning assessments, which are often a downward extension of adult-version tests, are hindered due to low construct validity and the lack of a developmental perspective. Low construct validity is the result of assessments tapping into multiple components of executive functioning, which further clouds the understanding of typical development within specific elements of higher cognitive functions (Brocki & Bohlin). It is also imperative to take into consideration the difficulty in devising "pure" executive functioning tasks. Similar assessment measures, that purportedly test the same executive skill area, may actually be assessing different cognitive facilities for children at different ages. Depending on the skill being assessed and the type of assessment, the subcomponents of executive functioning "possess different developmental trajectories and potentially mature at different rates" (Romine & Reynolds, 2005, p. 199). Given these difficulties it is oftentimes more useful to examine the qualitative nature of a child's assessment profile (i.e., the processes that a child uses to accomplish a task) rather than the quantitative index scores (Hughes & Graham, 2002).

Despite the immature development of executive functions in early childhood, Espy, Kaufmann, Glisky, and McDiarmid (2001) state that it is still important to assess these skills as long as the tasks that are utilized are developmentally appropriate. Assessing executive functions in young children is crucial due to the fact that so many disorders manifest before the child reaches school age (e.g., ADHD, autism, genetic disorders, etc.). With the vital benefits of early intervention, it is essential to assess current functioning abilities in order to develop appropriate programming (Espy et al.). As discussed in the previous section on development, rapid changes are taking place during early childhood in the prefrontal cortex. Increased coherence in anterior regions of the brain, as well as lengthened frontal-lateral connections, signifies substantial developmental growth occurring during the first five years of life (Thatcher, 1994).

Brocki and Bohlin (2004) note that historically most theories related to executive functioning were based on frontal lobe functioning in adults. However, recent interest in developmental factors associated with executive functions has fueled research and assessments designed specifically for children. Anderson (1998) also emphasizes the importance of reliable norming practices in tests developed for children, as well as increasing the "child friendly" procedures used during testing. Anderson states that the interpretation of tests should not be limited to composite scores; rather, analyzing the process that the child used to come to an answer may provide more information with respect to the specific subcomponents of executive functioning.

The NEPSY (Korkman, Kirk, & Kemp, 1998), and its subsequent revision the NEPSY-II (Korkman, Kirk, & Kemp, 2007), was the first developmental neuropsychological battery specifically designed for children. Rather than a downward extension of a battery originally designed for adults, the NEPSY-II takes into consideration the enormous influence that development plays in neuropsychological processes. The NEPSY-II is unique in that it measures the subcomponents of complex neuropsychological processes in children ages 3-years to 16-years, 11-months and has a strong theoretical basis in Luria's functional model. Lurian theory states that complex cognitive processes can be compared to a complicated system where impairments in one subcomponent affects performance in other higher order functional domains (Kemp, 2007). On the NEPSY-II there are six functional domains that assess neuropsychological processing in the areas of Executive Functioning, Language, Sensorimotor Functions, Visuomotor Processing, Memory and Learning, as well as Social Perception (Korkman et al., 2007). The subtests of the NEPSY-II that specifically measure the core components of executive functioning examine strategic planning abilities, flexibility, and self-regulatory processes. The NEPSY-II also measures the subcomponents within executive functioning of initiation, fluency, inhibition, and working memory (Kemp). Quantitative outcomes, as well as qualitative behaviors, are noted during the NEPSY-II that are compared against the norming sample and used for interpretative purposes (Korkman et al.).

While the NEPSY-II examines executive functioning, together with other multiple domains, the first comprehensive assessment specifically examining executive functioning was the Delis-Kaplan Executive Function System (D-KEFS) (Delis, Kaplan, & Kramer, 2001). The D-KEFS was normed on a large representative sample, and is designed to assess individuals ranging in age from 8-years to 89-years-old. The D-KEFS is a battery of nine independent tests designed to measure specific aspects of executive functioning through the use of verbal and non-verbal stimuli (Delis et al.). Individualized strengths and weaknesses can be examined through a process approach in measuring the foundational and higher-order thinking skills involved in executive functioning. The D-KEFS assesses skills related to executive functioning such as mental flexibility, verbal and visual fluency, behavioral initiation, concept formation, rule learning, and planning abilities (Delis et al.).

Stand alone tests have also been developed to examine characteristics associated with executive functioning. For example, the Wisconsin Card Sorting Test (WCST) (Heaton, 1981) measures problem solving, mental flexibility, inhibition, and goal-directed behavior. The WCST requires the individual to match one of four cards by a specific characteristic such as color, shape, or number. After ten correct trials the rule is changed by the examiner and the individual has to adapt and sort by a new rule. Other popular stand alone measures of executive functioning include the multiple adaptations of the Tower test (i.e., Tower of London, Shallice, 1982; Tower of Hanoi, Simon, 1975). Tower tests require an individual to plan the placement of a ball on pegs within a specific number of moves (Semrud-Clikeman, 2001). Tower tests assess organizational strategies, problem-solving abilities, and initiation or inhibition of motor responses. The Stroop Color Word Test (Stroop, 1935) evaluates executive functioning in relation to inhibitory responses. The test has three portions where the child reads the printed word, then identifies the color of the word, and then states the color ink that the word is printed in rather than the word itself. This final step of the Stroop Test requires the individual to inhibit automatic, over-learned responses (i.e., reading a word) and replace that response with stating the color of ink of the word (Semrud-Clikeman).

Additional stand alone measures of executive functioning include the Rey-Osterrieth Complex Figure (Meyers & Meyers, 1995). This measure specifically assesses executive control in the areas of visual-motor integration and visual memory. For this task, individuals are shown a figure stimulus and then asked to copy the stimulus from memory (Meyers & Meyers). Other components of executive control, such as task switching, visual motor tracking, and flexibility can be assessed through the use of the Trail Making Test (Partington & Leiter, 1949; Reitan, 1971). The TMT is a neuropsychological assessment procedure used for a number of years with both children and adults. Initially known as The Test of Distributed Attention, it was later renamed the Partington's Pathways Test, and had clinical use as a diagnostic tool for the assessment of brain injury in adults (Partington & Leiter; Watson, 1949). The Partington's Pathways Test was also included in the Army Individual Test Battery (1944), where it received its current name of the Trail Making Test (TMT). It was later included, with minor modifications, into the Halstead-Reitan Neuropsychological Battery (Reitan & Wolfson, 1985) where it continues to be used. Despite its age, the TMT continues to be among the most frequently used neuropsychological tests in clinical practice, as well as in research settings (Rabin, Barr, & Burton, 2005).

The TMT is used to assess a number of neurocognitive abilities including psychomotor speed, complex attention, visual scanning, and mental flexibility. This widely used measure of neuropsychological processing consists of two trails tasks. On Trails A the examinee must draw a consecutive line through numbered circles on a page. For Trails B the task difficulty increases as the examinee must now switch between drawing from a letter to a number and then returning to a letter in the appropriate sequence (Lezak, 1995). For example, a correct line would start at 1, and then proceed to A, then 2, then B and so on. The individuals are asked to complete the task as quickly as they can. Scores are based both on task accuracy and completion time (Lezak). The TMT has been repeatedly demonstrated to be sensitive to brain injury in children and adults (Boll et al., 1977; Jaffe et al., 1993; Reitan, 1955, 1971). Reitan and Wolfson (2004) utilized the Trail Making Test for Children (Reitan & Wolfson, 1992) to explore the usefulness of the TMT as a screening measure for children with neurocognitive deficits. Three groups of children between the ages of 9- and 14-years-old were tested. Group one consisted of children with known neurological damage or disease. The second group was composed of children who were physically healthy yet referred because of inadequate academic progress. The third group consisted of the typical developing control group.

Results revealed that the neurologically-impaired group needed three times the number of seconds to complete the task, and the academically-delayed group required two times the number of seconds as compared to the control sample. These outcomes demonstrate that the TMT is generally sensitive to neurological impairments; however, the etiology or biological basis for the poor performance is difficult to differentiate. Reitan and Wolfson (2004) concluded that the TMT is useful as a screening measure for determining those individuals who may need more intensive neuropsychological testing, but additional validation is necessary to identify the underlying deficits.

The D-KEFS (Delis et al., 2001) discussed earlier in this review also includes a trails measure. Given that each of the D-KEFS subtests are independently standardized, the trail making test within this battery can be administered in isolation. The D-KEFS Trail Making Test utilizes five conditions with the primary executive functioning task being the fourth condition. Condition 4 is similar to Trails B of the original TMT where the examinee is required to switch between letter and number targets as a means of assessing cognitive flexibility and switching. The other four conditions allow the examiner to isolate possible skill deficits that may be affecting the individual's overall executive functioning. Condition 1 begins with a simple visual scanning task. Testing proceeds to Condition 2 where the examinee is required to complete a number sequencing task, which is followed by a letter sequencing task in Condition 3. Condition 4 involves the executive functioning task of number-letter switching. The test concludes with Condition 5 which is a motor speed task. This last condition is present to assist the examiner in determining whether motor deficits may be the cause of a low score on Condition 4 rather than a true executive dysfunction.

As is evident in this review, trail making tests have been consistently utilized in various forms within neuropsychological batteries. However, the drawbacks in the original TMT hindered its ability to generalize across clinical and control group samples due to weak normative data and poor reliability statistics (Moses, 2004). The Comprehensive Trail Making Test (CTMT) was designed to off-set many of these psychometric deficits (Reynolds, 2002). Based on a standardized norming sample that included children and adolescents, the CTMT enhances and expands on the original trails measure by utilizing five trails instead of two. The five trails increase at various levels of difficulty to measure resistance to distraction, inhibition, task switching, and cognitive flexibility (Reynolds). Given this increased specificity, the CTMT is specifically useful for detecting “frontal lobe deficits, problems with psychomotor speed, visual search and sequencing, and attention; and impairments in set-shifting…” (Reynolds, p. 5). Gray (2006) states that despite the similarity of the CTMT with the original TMT, it is unique in that it “introduces distracter objects and a cognitive set-shifting element that was not part of the original test” (p. 91). Table 1 describes the components of each trail on CTMT.

Trail 1 of the CTMT is similar to Trails A in the original version where the examinee is timed while connecting a line from the numbers 1 through 25. This type of task taps into an individual’s ability to sustain attention while utilizing visual-scanning and sequencing abilities (Moses, 2004). Trails 2 and 3 build on the original Trails A; however, the difficulty is increased due to additional distractor circles. This requires the examinee to resist distraction and inhibit responses to the distractions. Reynolds (2002) states that both the simple (Trail 2) distracters and the complex (Trail 3) distracters increase the complexity of the selective and sustained attention necessary to be successful on this task. Trail 4 on the CTMT adds an additional cognitive demand by utilizing numbers in both the numeric form (e.g., 2, 4) and the written word (e.g., two, four). The numbers are represented arbitrarily between the English word and the Aramaic symbols which requires the examinee to inhibit responses and shift-set in a random pattern.

Table 1

Description of the Five Trail-Making Tasks of the CTMT

Trail 1	The examinee is required to draw a connecting line in order to the numbers 1 through 25. Each of the number targets are contained in a plain black circle.
Trail 2	The examinee is required to draw a connecting line in order to the numbers 1 through 25. Each of the number targets are contained in a plain black circle. There are twenty-nine empty distractor circles added to the visual array.
Trail 3	The examinee is required to draw a connecting line in order to the numbers 1 through 25. Each of the number targets are contained in a plain black circle. There are thirteen empty distractor circles and 19 distractor circles that contain extraneous line drawings added to the visual array.
Trail 4	The examinee is required to draw a connecting line in order to the numbers 1 through 20. Eleven of the numbers are presented in numeric form (e.g., 5, 9) and the remaining numbers are spelled out in written language (e.g., eight).
Trail 5	The examinee is required to draw a line in alternating sequence to connect the numbers 1 through 13 and the letters A through L. The line begins with the 1 and then continues to A, then 2, then B, and continuing until all of the numbers and letters are connected. There are fifteen empty distractor circles added to the visual array.

Note. Adapted from Reynolds (2002) *Comprehensive trail making test: Examiner's manual.* Austin, TX: Pro-ED.

Trail 5 necessitates switching between the numbers 1 through 13 and the letters A through L in an alternating sequence. Empty distractor circles are added to the visual array to increase the task-switching difficulty (Reynolds). The CTMT also differs from the original trails measure by increasing the complexity of the spatial arrangement. Rather than following a path that proceeds gradually out from the center, the CTMT varies the directionality of the target stimuli in their given sequence. This enhances the complexity of the CTMT to provide an assessment that more effectively measures executive functioning skills such as visual spatial scanning, sequencing, cognitive flexibility, processing speed, and perceptual-motor integration (Moses).

The CTMT is designed for use with individuals between the ages of 11 years, 0 months and 74 years, 11-months-old (Reynolds, 2002). An ability to understand the verbal directions, and complete the sample items, are necessary components for administration of the CTMT. If the examinee is unable to complete the sample item after multiple attempts the testing should not be continued. Sample A is a screening task to be used before Trails 1, 2, and 3 are administered. The half-page sample task requires the examinee to draw a connective line through the numbers 1 to 5 while ignoring six distracter circles. Two distracter circles are blank and four distracters contain extraneous designs (Reynolds). Successful completion of Sample A allows the administration of Trails 1 through 3. Sample B is then presented as a screening measure before Trails 4 and 5. The half-page sample task consists of three rectangles with a printed word inside of them and five circles which contain a numeric symbol. Two distracter circles are also included in the visual array. The examinee is asked to draw a contiguous line from circle to rectangle to circle in the correct numerical order until the end of the sequence (Reynolds). If Sample B is successfully completed then the testing continues to Trail 4. Sample C is administered before proceeding to Trail 5. This screening task consists of nine circles that contain either the letters A through D or the numbers 1 through 5. The examinee is required to connect the circle in correct order by alternating between the letters and numbers (e.g., 1-A-2-B). If Sample C is successfully completed Trail 5 is administered. Administration of the five trails and sample tasks takes approximately 10 minutes. Interpretation should only be completed by those formally trained in test administration and scoring, along with a thorough understanding of brain functioning, neuroanatomy, and neuropsychology (Reynolds).

The response time on each trail is recorded and errors are corrected as they occur. The types of errors are not scored; however, errors affect the overall performance in that they require additional time for correction to take place. The results of the five trails combine to provide an overall Composite Index. Norms for each trail and the Composite Index are presented in the form of *T*-scores, which have a mean of 50 and a standard deviation of 10. Reynolds (2002) states that the individual trails *T*-scores are "age-corrected deviation scaled scores based on the cumulative frequency distributions of the raw scores" (p. 19). These scores are calculated based on the percentages linked to the raw scores in the standardization sample. Both the raw scores, and the standard deviations, were computed at 1-year intervals for the ages of 11- through 19-years-old to account for developmental influences. The adult age ranges were based on ten year increments (e.g., 20-29, 30-39, etc.). At each age interval the raw scores were converted to *T*-scores to allow for consistency across age levels.

Despite the benefits and usefulness of the CTMT, few studies have been conducted to validate this measure. The sensitivity and specificity of the CTMT was examined by Armstrong, Allen, Donohue, and Mayfield (in press) with a cohort of children and adolescents who had sustained a traumatic brain injury. The 30 TBI participants were matched to 30 healthy control subjects on age, gender, ethnicity, and geographic location. Results revealed that the TBI sample demonstrated scores approximately 2 standard deviations below the control sample mean on all five of the CTMT trails, as well as on the Composite Index. The level of differences between the clinical and control groups was significant ($p < .001$). Given the small sample size, Armstrong and colleagues were not able to conduct a factor analysis with the clinical group; however, the patterns of correlations of each trial were examined. The TBI sample demonstrated somewhat higher correlations than the healthy control group between Trails 1 and 4, and Trails 3 and 5. Specificity analyses revealed that Trail 5 and the Composite Index proved to be the strongest measures for classification accuracy between the TBI and control groups. Armstrong, Allen, Donohue, and Mayfield state that the evidence for the CTMT demonstrates comparable results to the sensitivity and specificity of the adult and child versions of the original TMT. However, direct comparisons are difficult because of the standardization of the raw scores and the age correction techniques utilized in the CTMT. Despite the need for replication with a larger sample size, Armstrong, Allen, Donohue, and Mayfield conclude that the results demonstrate strong sensitivity and overall utility of the CTMT with individuals who have sustained a TBI.

Traumatic Brain Injury in Children

Due to the hidden nature of cognitive deficits resultant from a brain injury, this public health problem is often referred as the "silent epidemic" (Langlois et al., 2006, p. 1). Each year in the United States, over a million individuals sustain a TBI resulting in 50,000 deaths and 235, 000 hospitalizations. Emergency room visits for head injuries toppled 1.1 million (Langlois et al.). While these numbers are staggering, there are many more individuals who sustain a TBI who do not seek medical care. The most common causes of TBI for all age groups are falls, motor vehicle accidents, struck by or against events, and assaults. See Figure 4 for a graph of the percentages of TBI injury related emergency room visits, hospitalizations, and deaths for the years 1995 to 2001. When examining the demographics of those who experience a TBI, the statistics reveal that males are 1.5 times more likely than females to sustain a head injury, and African Americans have the highest death rate as the result of a TBI. Additional risk factors include substance abuse and the presence of psychiatric conditions such as attention deficit/hyperactivity disorder (Kim, 2006). These premorbid conditions are associated with impulsive or high risk behaviors which potentially lead to TBI. The National Center for Injury Prevention and Control estimates that there are currently 5.3 million Americans who suffer from long-term or lifelong effects of a TBI and need assistance to perform daily living skills (Langlois et al.). These statistics are disheartening considering the two highest risk groups for TBI are children and young individuals. Adolescents between the ages of 15- to 19-years-old represent the highest risk category due to motor vehicle accidents.

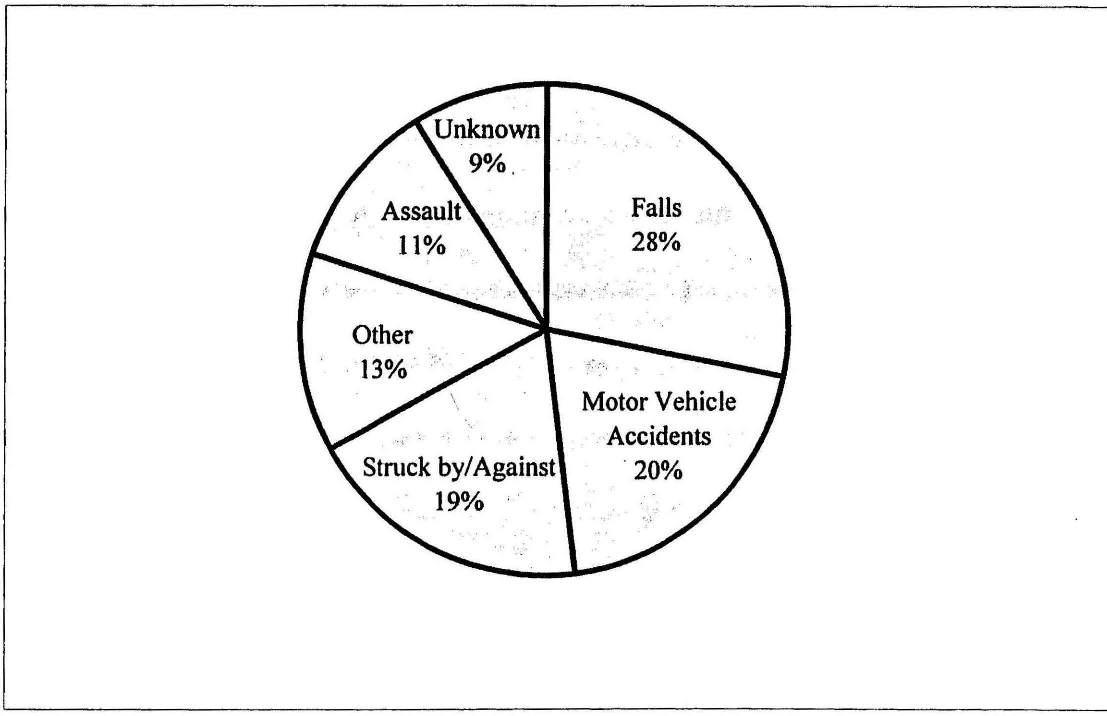

Figure 4. Annual Percentage of TBI related emergency department visits, hospitalizations, and deaths from 1995-2001.

Note. Adapted from Langlois, J. A., Rutland-Brown, W., and Thomas, K. E., *Traumatic brain injury in the United States: Emergency department visits, hospitalizations, and deaths*. Atlanta, GA: Centers for Disease Control and Prevention, National Center for Injury Prevention and Control, 2006.

The second highest category is young children between the ages of birth and 4-years-old due to falls. For elementary age children the most common causes of head injury are pedestrian and bicycle accidents (Semrud-Clikeman, 2001). Approximately 475,000 TBIs occur in children between the ages of birth and 14-years-old with 165,000 requiring hospitalizations (Langlois et al., 2006). The leading cause of death for children under the age of 15 is head injuries, which is significantly higher than the second leading cause for this age group of childhood leukemia (Semrud-Clikeman). Among those children who survive their injuries, significant delays are often seen across multiple domains. Given the developmental influences discussed previously in this review, the impact of TBI in children cannot be understated. The age of the child, as well as the location and severity of the injury, all determine which cognitive factors will be impaired. Disruption in any area may impact the development of new neural pathways as well as hinder the retrieval of information already learned (Semrud-Clikeman). For example, damage that takes place in the frontal or posterior regions of the brain may not be evidenced until the child reaches young adolescence and is expected to utilize the higher-order cognitive processes mediated in these regions.

Individuals with frontal lobe damage as the result of a TBI do not necessarily evidence deficits on traditional intellectual batteries (Hughes & Graham, 2002). This is possibly due to the fact that verbal abilities often remain relatively intact post-injury and most intellectual assessments are verbally-loaded. However, Slomine, Gerring, Grados, Vaso, Brady, Christensen, et al., (2002) found that verbal ability and executive functioning were not independent when examining 68 children between the ages of 7- and 15-years-old who had suffered moderate to severe head injuries. Results indicated that in children with diffuse brain injuries outcome measures of verbal abilities appeared to be assessing injury severity rather than intellectual ability (Slomine et al., 2002). An increased severity of head injury led to a greater deficit on intellectual measures. The amount of time between the injury and the assessment is another important variable to consider. For children and adolescents improvements can be demonstrated as the brain continues to recover for up to five years post-injury (Semrud-Clikeman, 2001).

The type of injury is an additional moderating variable that needs to be understood when examining brain injuries. A head injury can either be open or closed depending on the way the injury occurs. An open head injury is the result of an external object penetrating the skull (i.e., gunshot wound). A closed head injury results from the head striking a fixed object, falling, or physical abuse such as shaken baby syndrome. Acceleration or deceleration injuries can also occur with or without impact to the skull (Semrud-Clikeman, 2001). Within the classification of closed head injuries, damage can be either focal or diffuse. A focal injury is typically due to the impact of the head with a stationary object resulting in a skull fracture or brain contusion. In children this is usually seen through bicycle injuries. Damage during a focal injury is at the point of impact, which is termed the coup. The brain rebounds due to the force and creates a countercoup injury on the opposite side of the brain, which often results in a hematoma (Semrud-Clikeman).

Diffuse injury results when there is shearing of the white and gray matter in the brain. This is generally caused by the stretching of the axons due to the acceleration or deceleration of the brain most frequently caused by car accidents or child abuse (Semrud-Clikeman, 2001). Shearing and diffuse axonal injury occur due to tissue compression and extension that leads to a tear or rupture of the axon (Bigler, 1997). The axon may then retract and degenerate resulting in cell death and subsequent loss of functioning. Shearing may also result in hemorrhagic lesions or bleeding due to the rupture of capillaries in the brain (Bigler, 1997). Shearing effects are most often seen at the gray matter and white matter junctions in the brain (Bigler). These injuries that are the direct result of the trauma are considered primary effects. However, secondary effects can also occur after the injury and affect the recovery process. An example of a secondary effect would be the brain swelling and causing an additional hemorrhage, subdural hematoma, or areas of ischemia (Semrud-Clikeman)

Executive Functioning and Traumatic Brain Injury in Children

The evaluation of children who sustain a significant head injury often presents unique challenges as a result of the injury. A comprehensive neuropsychological battery is usually necessary to examine functioning levels across various domains and to plan intervention strategies. An initial assessment for a child following a TBI is difficult due to the multiple factors that influence outcomes. The child's developmental level and premorbid functioning have to be taken into account, as well as the location and type of injury (Semrud-Clikeman, 2001). When a young child experiences a head injury it not only disrupts the developmental process, but it also initiates a parallel process of recovery. These congruent processes of development and recovery are intertwined and continue to interact as the child matures (Farmer et al., 1997).

Ylvisaker and DeBonis (2000) state that "executive system impairment is often the most debilitating disorder after TBI" (p. 35). Depending on the type of injury, the location of the frontal lobes is highly susceptible to the detrimental effects of a TBI. The bony protuberances at the base of the frontal lobes, and the frontal-temporal regions inside the skull, increase the vulnerability of the frontal lobes (Ylvisaker & DeBonis). An insult to the frontal lobes at any age can have significant consequences later in development given the protracted developmental process which continues through adolescence. Unfortunately, children may often "grow" into their deficits depending on what type of skill deficit is being examined. The individual's deficits may not be demonstrated until the injured brain area is needed to support a developmental transition (Ylvisaker & DeBonis). The type of injury is also a moderating factor given data that states that young children more often experience a TBI due to a fall, while older children have a higher likelihood of sustaining an injury as the result of motor vehicle accident (Langlois et al., 2006).

It is important to note that deficits after a childhood TBI may not initially be seen on a traditional intellectual test due to the verbally-loaded content of the test measures. Given that verbal abilities have been found to be fairly stable after a TBI, a traditional ability test may not adequately reflect non-verbal deficits (Semrud-Clikeman, 2001).

While this strength in verbal abilities can be utilized, it often masks underlying deficits as the child appears to be functioning at a higher level than is readily apparent. It has also been suggested that traditional, standardized procedures during testing may inflate outcome scores due to the minimal distractions and one-on-one attention provided (Slomine et al., 2002). When assessing executive functioning deficits after a TBI, the additional environmental cues, such as the examiner providing clear instructions and guiding the process, may led to an increase in scores on a generalized measure of intelligence. Lezak (1995) states that the structured nature of standardized tests may not accurately tap executive functions and argues that qualitative behaviors demonstrated during testing may be more beneficial. These qualitative observations, along with information provided by family and community sources, will provide valuable information outside of the standardized scoring results.

The effects of severity of injury and time since the injury were examined in a study completed by Brookshire, Levin, Song, and Zhang (2004). Brookshire and colleagues compared children who had experienced a TBI (*n*=286) in comparison to typically developing children (*n*=104) on a series of executive functioning tasks. Those in the clinical group included 62 mild, 90 moderate, and 134 severe TBI patients who were grouped based on their initial Glascow Coma Scale and were tested at least 36 months post-injury. Multiple measures were used to measure problem-solving, planning, processing speed, memory, response inhibition, and language functioning. Exploratory factor analysis on twenty factors revealed five primary factors (Brookshire et al., 2004).

Factor one was termed Discourse and was defined by language measures and oral receptive vocabulary. Factor two, entitled Problem-Solving included measures which purportedly assess planning, productivity, working memory, and metamemory. The third factor of Processing Speed included reaction time measures, rapid picture naming, and speed of word generation. Factor four, which was termed Declarative Memory, was comprised of measures that tapped into recall of words and the organization of semantic memory. The fifth factor, Motor Speed, was comprised of dominant hand performance time and total time on a motor sequencing task (Brookshire et al.).

An additional exploratory factor analysis was then completed with children who had experienced a TBI, but this cohort was tested at 3-months post-injury (versus the 36 month post-injury testing in the previous cohort). This revealed a four factor model including Discourse, Problem-Solving, Processing-Motor Speed, and Declarative Memory (Brookshire et al., 2004). When accounting for age and severity of injury (i.e., mild, moderate, or severe) both variables were significant for the five factor and the four factor models. No interaction effects were noted between age at testing and severity, or age at injury and severity of injury. The authors conclude that these results provide a thorough overview of the underlying constructs of executive functioning in children with TBI. These factors could help provide the basis for choosing assessment measures specific to the executive functioning area of interest (Brookshire et al.).

Summary

The potential long-term detrimental effects of traumatic brain injury should fuel researchers to continuously pursue stronger assessment techniques and intervention strategies. Given the interaction between the neurological insult and developmental trajectories, brain injuries in children are a crucial area of study. With the recent addition of measures specifically designed for children, assessment practices are increasing in specificity. However, research is still needed to continue to evaluate the effectiveness of these measures with identifiable clinical populations. The research related to children who have experienced a TBI is emerging; yet with gaps related to the interaction effects of age, and type or severity of the brain injury. As this review has demonstrated, additional research is imperative to parcel out the effects of a neurological insult on the subcomponents of executive functioning. While it is evident that frontal lobe deficits affect multiple areas of functioning, it remains unclear the long-term effects of specific executive deficits such as task-switching, inhibition, and cognitive flexibility. The findings of the present investigation provide a deeper understanding of executive functioning in children who have experienced a traumatic brain injury. As a result, additional knowledge is available for practitioners, parents, or educators who work with children with a brain injury to assist in developing appropriate assessment and intervention strategies.

Hypotheses

The following hypotheses were proposed to accomplish the purpose of this study:

1. Comparison between the TBI and matched control group on the CTMT Index score. It is hypothesized that there will be no statistically significant difference between the TBI group versus the control group on the CTMT composite index score.
2. Comparisons between the TBI and matched control group on the Trails that comprise the CTMT Index score.
    a. It is hypothesized that there will be no statistically significant difference between the TBI group versus the control group on the CTMT Trail 1 score.
    b. It is hypothesized that there will be no statistically significant difference between the TBI group versus the control group on the CTMT Trail 2 score.
    c. It is hypothesized that there will be no statistically significant difference between the TBI group versus the control group on the CTMT Trail 3 score.
    d. It is hypothesized that there will be no statistically significant difference between the TBI group versus the control group on the CTMT Trail 4 score.

e. It is hypothesized that there will be no statistically significant difference between the TBI group versus the control group on the CTMT Trail 5 score.

3. Comparisons between the TBI group and control group, both individually and combined, on groupings of trails.

    a. It is hypothesized that there will be no statistically significant difference between the TBI group versus the control group on the CTMT Trails 1 through 3 averaged score.

    b. It is hypothesized that there will be no statistically significant difference between the TBI group versus the control group on the CTMT Trails 4 through 5 averaged score.

    c. It is hypothesized that there will be no statistically significant difference within the TBI group on the combined average scores of the CTMT Trails 1-3 vs. Trails 4-5.

    d. It is hypothesized that there will be no statistically significant difference within the control group on the combined average scores of the CTMT Trails 1-3 vs. Trails 4-5.

4. Comparison of the factor structure obtained from the TBI clinical group to the two-factor model that was present in the CTMT standardization sample. It is hypothesized that the results of the TBI group will reveal two distinct factors comprised of Trails 1-3 and Trails 4-5.

CHAPTER III

METHODS AND PROCEDURES

Procedures

The participants for the current study consisted of 160 cases drawn from a clinical sample of individuals who had sustained a traumatic brain injury and a matched control group taken from the standardization sample of the CTMT. Participants were children and adolescents between the ages of 11- and 19-years-old. The data for the TBI clinical sample was collected from records at Our Children's House at Baylor, which is a pediatric specialty hospital located in Dallas, Texas. The control sample was obtained from the CTMT author and publisher, and matched on age and gender with the clinical sample. The ethical standards of practice set forth by the Institutional Review Board Texas Woman's University were maintained throughout the current study.

Clinical Group Participants

The participants in the TBI sample had experienced a significant insult to their brain as confirmed by MRI or CT scans. Approximately five to twenty months post-injury, children who had sustained a TBI completed a formal neuropsychological evaluation to determine current level of functioning. The neuropsychological assessment was comprised of measures evaluating intellectual abilities, academic achievement, attentional processes, visual-motor skills, and behavioral regulation. Depending on the child's level of competency, the assessment took approximately four to six hours to complete. The order of the assessment measures was dependent on the needs of the child taking into consideration factors such as fatigue, need for breaks, and the child's overall response to the assessment situation. The neuropsychological evaluation was completed by professionals trained in standardized administration of the measures. The standardized instructions and administration procedures were utilized, as depicted in the CTMT manual (Reynolds, 2002).

The data for the TBI clinical group was collected from the outpatient records at Our Children's House. This data was then coded and entered into a pre-established database. Identifying information was maintained in a separate database and kept blind to the primary researcher. Once the data was entered into the database, a validity check was conducted where 10% of the entered files were reviewed for accuracy. Each set of files was chosen based on a random number generator. If errors were identified, those files were corrected and a new set of 10% were randomly chosen. This process was continued until no errors were detected.

Control Group Participants

The participants in the control group were drawn from the normative sample of the CTMT (Reynolds, 2002). In an attempt to control for the interaction of developmental variables, the comparison sample was matched in age with the TBI sample. Potential gender differences were also controlled for by matching the TBI sample with the control sample. Those individuals in the TBI sample were selected for inclusion in the study based on several factors. The participants who did not complete all five trails of the

CTMT were excluded. The remaining sample was separated by gender and age to determine the matched control group sample. The control group was then randomly matched, using a random number generator, on age and gender to the clinical group. Demographic information for the TBI group was obtained from the individual's medical file at Our Children's House at Baylor. The demographic information for the control group was obtained through the CTMT normative data.

Measures

Executive Functioning

As previously discussed in this review, the assessment of executive functioning in childhood is a daunting task. Broad-based neuropsychological measures often assess executive control as a subcomponent within a full battery. There are also multiple stand-alone type measures that assess specific characteristics of executive functioning. The CTMT (Reynolds, 2002) was utilized for the current study. The CTMT taps into executive control in the areas of selective and divided attention, mental set-shifting, inhibition of responses, and sequencing abilities. The CTMT enhances the original trails measure by utilizing five trails instead of two. The five trails increase at various levels of difficulty to measure resistance to distraction, inhibition, task switching, and cognitive flexibility (Reynolds). Trail 1 is analogous to Trail A and Trail 5 is similar to Trail B of the original TMT. Reynolds states that this increased specificity helps to determine specific areas of deficit.

The CTMT is normed on a large, demographically representative sample from four major geographic regions of the United States. The CTMT was standardized on 1,664 individuals based on a stratified random sampling matched from the 1998 U.S. Bureau of the Census population statistics. The normative sample was drawn from 19 states representative of the four major geographic regions of the contiguous United States. Gender was evenly distributed and ethnicity was closely matched based on the census data. Demographic variables, such as family income level, disability status, age, and educational level of parents of child participants, as well as the education of the adult participants, were factored within the normative sample and reflective of the census data (Reynolds, 2002). The CTMT sample was "meticulously chosen and is widely representative of the current American population on all of these key demographic characteristics" (Moses, 2004, p. 705).

Reliability of the CTMT

The reliability of a measure is the consistency and accuracy with which that measure correctly identifies the attributes it is seeking to assess. Reynolds (2002) states that the reliability of a test measure is foundational to the practicality and usefulness of all types of assessments. If the construct that is being measured is stable, there will be high reliability regardless of intervening variables such as time, setting, sample or administration by various examiners. Without strong reliability an examinee could evidence deficits on one day but surprisingly be "cured" when assessed at a different time. The opposite is also true where the examinee could not be identified as having a true deficit when one exists due to poor reliability of the testing measure utilized.

Three types of reliability were examined on the CTMT. The first type of reliability analyzed the consistency between test items. Content sampling is used to determine the similarity of the content, in that the more the items relate to each other the lower the error in the test will be. When test items are unrelated to each other it is likely that different skill areas are being measured. Due to the speeded nature of the CTMT, alternate-form reliability was utilized to measure internal consistency (Reynolds, 2002). All raw scores were converted to *T*-scores before calculating reliability to account for developmental changes. Each of the CTMT trail scores reach at least .70 for the total sample score. The reliability coefficient for the CTMT Composite Index exceeds .90 for the total sample. The Composite Index for the gifted and learning disabled children subgroups, as well as for adults who had experienced a cerebrovascular insult, demonstrated internal consistency coefficients all above .90. Gray (2006) states that the reliability data of the CTMT is within acceptable limits; however, the reliability coefficients for each individual subtest may not be high enough to allow diagnostic interpretations. See Table 2 for the individual internal consistency coefficients for each trail and the Composite Index for the overall sample.

Table 2

Overview of the CTMT Reliability Related to Three Sources of Test Error

	Sources of Test Error		
CTMT Trail	Content Sampling	Test -Retest	Score Reliability
Trail 1	.74	.74	.98
Trail 2	.77	.78	.98
Trail 3	.72	.72	.96
Trail 4	.70	.70	.98
Trail 5	.70	.75	.96
Composite Index	.92	.84	.99

Note. Adapted from Reynolds (2002) *Comprehensive trail making test: Examiner's manual.* Austin, TX: Pro-Ed.

The second type of reliability utilized with the CTMT was a time-sampling technique. Test-retest reliability refers to the consistency of an individual's scores across time. Individuals in the norming sample were tested on the CTMT and then re-tested one week later. Raw scores were again converted to *T*-scores to control for age related differences. Test-retest reliabilities across all five trails were above .70 with the Composite Index at .84. This demonstrates that the Composite Index is a more consistent measure across time. Practice effects must also be taken into consideration. Reynolds (2002) states that as the "complexity and novelty of the task increases, so does the practice effect" (p. 28). Given that the CTMT is both novel and primarily non-verbal the likelihood of practice effects is probable. See Table 2 for the overall test-retest reliability for the each trail and the Composite Index of the CTMT.

The third type of reliability investigates the possible error due to examiner variability in scoring. When agreement between examiners is high there is a lower likelihood of error due to inconsistent scoring (Reynolds, 2002). To account for potential scorer differences, two independent examiners scored a randomly selected subset of the CTMT. The raw scores were converted to *T*- scores to take into consideration age related differences. All coefficients were above .96 indicating high reliability of scoring of the CTMT by trained examiners. The Scorer Reliability is listed in Table 2 for each individual trail as well as the overall Composite Index of the CTMT.

Validity of the CTMT

Validity is defined by Reynolds as the "appropriateness and accuracy of the interpretation of a performance on a test" which will "vary according to the purpose for which test scores are being used" (2002, p. 31). The interpretation of the CTMT is established by theory-based evidence as well as empirical evidence. The theory-based evidence is derived from the conceptualization of the brain based on Luria's functional units. The interrelated systemic network of the brain demonstrates the importance of neurological integrity for optimal performance (Luria, 1976). Damage or disease within a component of the interdependent system may lead to dysfunction within a different domain. Luria (1976) conceived the frontal lobes as the "superstructure" for the executive control center of the brain. The CTMT taps into multiple areas of functioning that are dependent on efficient frontal lobe processing. The CTMT measures executive control tasks such as sustained and selective attention, complex sequencing, decision-making, inhibition, as well as mental set-shifting. Reynolds (2002) emphasizes that the CTMT is "intended not only as a measure of frontal lobe function, but also as a measure of overall neuropsychological integrity" (p. 33).

The validity of a measure is often examined based on an instrument's content, the construct being measured, and the relationship between the test scores and variables external to the test. Content validity is assessed by comparing the stimuli and format of the CTMT to other similar tasks. Lezak (1995) states that trail making tasks tap into complex executive functions such as visual scanning, motor speed, information processing, and attention. As a sensitive measure to these executive control tasks, trail making tests have been deemed important in assessing concentration deficits and in detecting frontal lobe defects (Lezak). Reynolds (2002) discusses the interrelated nature of the CTMT stimuli and the response of the examinee. Despite the difficulty of not being able to "observe" executive processes such as attention, set-shifting, or inhibition, the method of responses are consistent with the proposed constructs. The completion time on each trail demonstrates key characteristics of functioning in the areas of attention, concentration, and resistance to distraction (Reynolds). This result is then influenced by sequencing demands and set-shifting abilities. Deficits in any of these areas are hypothesized to be evidence of possible frontal lobe dysfunction.

The second major assessment of validity examines construct validity. High construct validity demonstrates that a test accurately measures the construct that it is designed to assess. Given that the CTMT was developed to remedy the psychometric short-comings of the original Trail Making Test, the CTMT elaborates on the original measure by utilizing five trails rather than two. This increased specificity is "designed to highlight and isolate specific components of performance" (Moses, 2004, p. 703). The CTMT is intended to measure subcomponents of executive functioning in the areas of task-switching, inhibition, selective and sustained attention, speed of processing, and visual-spatial integration (Reynolds, 2002). Internal validity was assessed using an exploratory factor analysis to obtain an intercorrelation matrix for the five trails. The results of the factor analysis demonstrated two primary factors. The primary factor is hypothesized to represent the stated distinction between Trails 1 through 3 and Trails 4 and 5 (Reynolds). The initial trails 1 through 3 require a connection within a singular concept. Whereas Trails 4 and 5 necessitate an increased demand for shifting between concepts while maintaining sequences. The overlapping skills between all five trails include the requirements for attention, visual scanning, and the integration of visual motor abilities. The primary factor was termed Simple Sequencing (i.e., Trails 1 through 3) while the second factor was designated Complex Sequencing (i.e., Trails 4 and 5). These factors remained evident when examined across gender, age, and ethnicity (Reynolds). Overall, the strong construct and high content validity of the CTMT provides support for its claims as a measure of neuropsychological processing integrity.

Validity can also be measured by evaluating the relationship between the test's scores and external variables. External validity can be measured by comparing tests which purportedly measure similar or dissimilar constructs, and through comparing other external variables such as diagnostic categories or developmental constructs. Multiple external variables were investigated with the CTMT which include age, status variables, as well as the CTMT's relation with other tests (Reynolds, 2002). Age related variables demonstrated a common pattern. On all of the trails measures, scores increased with age from 11-years-old through age 29-years-old. The author indicated that this rapid change is due to the developmental maturation of the frontal lobes during this developmental period. This natural curve begins to downturn around the age of 30 and continues to decline consistently through the age of 75-years-old (Reynolds). The most striking declines occur after the age of 60. These results demonstrate the importance of utilizing age-related norms when assessing executive functioning skills.

Criterion validity was also evaluated through the use of comparison measures. Subsets of individuals within the standardization sample were given three other types of measures to determine their correlation with the CTMT. The Developmental Test of Visual Perception-Adolescents and Adults (DTVP-A) (Reynolds, Pearson, & Voress, 2002) was given to a portion of the norming sample. The DTVP-A measures skills such as visual-motor integration, scanning, and perceptual processing. Results indicated strong correlations between these two measures demonstrating that the CTMT is likely influenced by visual perceptual abilities. Statistical significance was demonstrated at the $p \leq .01$. Correlational analyses of the CTMT demonstrate similarity with other instruments that measure motor speed and visual perception skills (Moses, 2004).

External validity of the CTMT was also examined using the Rey Complex Figure Test and Recognition Trial (RCFT) (Meyers & Meyers, 1995). The RCFT is a nonverbal measure which assesses memory recall and copying abilities. Comparisons between the RCFT and the CTMT indicated no significant correlation between the copying portions of the RCFT. However, low correlations were demonstrated on the recall component. Reynolds (2002) states that this correlation is likely the result of the small working memory factor that is necessary to retain the next item in the short term memory hold in order to continue the sequence on the trail. All participants in the standardization sample were given the Draw-A-Person Intelligence test (DAP:IQ) (Reynolds & Hickman, 2002).

This measure is a human figure drawing task. The DAP:IQ nonverbal intelligence score was compared against the CTMT Composite Index to yield a significant relationship. Statistical significance was demonstrated at the $p \leq .01$ level.

The validity of the CTMT has been confirmed by Servesko, Smith, and Edwards (2006) who examined the convergent, divergent, and discriminant validity of the CTMT. Data obtained from both outpatients (n=21) and non-clinical samples (n=61) compared results of the CTMT with other popular neuropsychological measures. Convergent validity was high with the DTVP-A (Reynolds et al., 2002) on measures of visualspatial processing, as well as with cognitive inhibition when using the Stroop test, and with performance IQ measures. Divergent validity was evident when comparing the CTMT with assessments measuring verbal intelligence. When assessing discriminate validity, the clinical and non-clinical groups differed on three of the five trails and the composite score. Servesko and colleagues concluded that the CTMT was a valid measure for assessing processing speed, visuomotor integration, and cognitive inhibition.

The influence of overall intelligence on outcome measures in neuropsychological batteries has been discussed previously in this review. The marginal correlations between IQ and measures such as the CTMT were demonstrated through examining the mean differences in outcomes with three special populations. Fifty-seven adolescents in a gifted and talented program for children with intelligence quotients over 120 were given the CTMT. Results demonstrated an average of .5 standard deviations above the mean of the normative sample (Reynolds, 2002). The influence of intelligence was also seen in the opposite direction when a group of adult participants, who had experienced a cerebrovascular accident (CVA), were also evaluated with the CTMT. This group scored significantly lower than any other subset with a Composite Index of 33. This score falls 1.7 standard deviations below the mean when compared to same age adults (Reynolds). A subset of adolescents who had been diagnosed as learning disabled (LD) also scored consistently below the normative sample. The LD group had a Composite Index of 42 which falls at .08 standard deviations below the mean (Reynolds). These results from the three subgroups provide support for the proposition that the CTMT is a solid measure of the overall neuropsychological integrity of the brain.

Data Analysis

The data was analyzed with respect to the research questions outlined in chapter two. The analyses of the data were completed using SPSS 15.0 (SPSS, Inc., 2007). The initial research question sought to determine if there was a significant difference between the TBI group and control group on the overall composite score of the CTMT. An analysis of variance (ANOVA) was utilized to compare the clinical group to the control group on the Composite Index. An ANOVA measures the differences between or among group means in order to determine the individual effects of each variable, as well as the interacting effects of two or more variables (Howell, 1997). This analysis determined if one or more of the means significantly deviated from one or more of the other means. Given that there are no restrictions on the number of means utilized, an ANOVA is preferable over a *T*-test in that the probability of type-I error can be held constant (Howell).

The use of the ANOVA is based on several assumptions. It is assumed that the populations being compared have the same variance, the observations are independent, and each score being examined is normally distributed around the mean. Independence of each observation is imperative in that knowing a change in one observation does not affect a change in another observation (Howell, 1997). Homogeneity of variance is important when comparing means of a group in order to control for possible effects related to error variance. Error variance is variance that cannot be accounted for by treatment or group differences (Howell). While this is an important factor, Howell states that "under certain conditions the assumption of homogeneity of variance can be relaxed without substantially damaging the test" (p. 303). The third assumption when using ANOVAs is that the variable being examined is normally distributed about the mean. This assumes that the variability of each participant's scores approximate the normal distribution. Howell points out that moderate deviations from this assumption can take place without destroying the test.

Secondly, the data was analyzed to determine if significant differences existed between the TBI group and the control group on each individual trail. The data to answer this question was examined through the use of a repeated measures multivariate analysis of variance (MANOVA). A MANOVA is an extension of the ANOVA; however, multiple dependent variables are now factored into the equation. While ANOVA is used to test whether mean differences among groups differ on one dependent variable, MANOVA examines whether mean differences within groups on a combination of dependent variables could have occurred by chance (Tabachnick & Fidell, 2001). The variance in scores is partitioned into the variance that can be attributed to the differences within groups and among groups. Means of each group are summed with the squared differences between scores to obtain a sum of squares. These sum of squares are divided by the appropriate degrees of freedom to provide estimates of the variance attributable to various sources, such as the main effects of the independent variable, interactions among independent variables, and possible error (Tabachnick & Fidell). These ratios of variance provide tests of hypotheses as to the likely effects of the independent variables on the dependent variables.

The third research question sought to determine if significant differences existed between the TBI group and the control sample on groupings of trails (e.g., Trails 1-3 vs. Trails 4-5). A repeated measures MANOVA was also utilized to answer this question. As with the ANOVA procedure discussed earlier, a repeated measures MANOVA tests the equality of means over several trials. However, a repeated measures MANOVA is used when all members of multiple groups are measured under a number of different conditions. As the groups are exposed to each condition in turn, the measurement of the dependent variable is repeated. This analysis allowed for comparisons between groups and between the individual trails measures. Differences were examined between the TBI and control group on the combination of Trails 1 through 3 and on Trails 4 though 5.

Also, within group differences were analyzed to determine if significant differences were present within the TBI group or within the control sample on the various groupings of trails.

Finally, the data was analyzed to confirm the findings of the two factor model reported in the CTMT standardization sample when using a sample of participants who had sustained a TBI. In the standardization sample, the first factor consisted of Trails 1-3, which was termed "Simple Sequencing," and factor two was comprised of Trails 4-5, which was labeled "Complex Sequencing." Due to a small TBI sample size, the Armstrong, Allen, Donohue and Mayfield (in press) research was not able to determine a factor structure. The current study utilized a larger cohort to assist in investigating the factor structure of the CTMT with a TBI clinical population.

To examine this question, confirmatory procedures were used to determine if variables within the set formed independent, cohesive subsets (Tabachnick & Fidell, 2001). The analysis summarized the data by grouping together relevant variables in order to test a hypotheses about underlying processes within each variable. The shared variance among variables was analyzed and the variance attributable to error or unique to each variable is eliminated (Tabachnick & Fidell). In the current study, the results were analyzed to confirm or refute whether the two factor model that was obtained with the entire standardization sample would remain consistent with a TBI cohort. An additional principal component analysis compared the factor structure of the matched control group to determine if it was consistent with the TBI group. The rotation method chosen was Varimax with Kaiser Normalization for an orthogonal factor matrix.

Research Design

This study was undertaken to determine the effects of TBI in children and adolescents on executive functioning using the CTMT. Independent variables for the current study consisted of the control group and the TBI group. The dependent variables were comprised of the various combinations of CTMT results on Trails 1 through 5 and the Composite Index. Given that the clinical group participants could not be randomly assigned, the control sample was randomly matched in age and gender to the clinical sample to enhance compatibility. By comparing matched groups, any observed differences on the CTMT are likely indicative of the impact of a TBI on specific characteristics of executive functioning.

In order to discuss the anticipated differences on the dependent variables, the potential threats to internal validity within this proposed study need to be addressed. Internal validity relates to the ability to draw conclusions of inferential relationships within the data. High internal validity demonstrates strong causal relationships between variables (Cozby, 1997). In the present study, the internal validity threat of instrumentation was reduced given that the assessment was administered according to standardized procedures by trained clinicians. Other possible threats to internal validity include history, testing, and regression (Campbell & Stanley, 1966). The impact of these threats are diminished since each participant was only given one trails measure. The most likely potential threat in the current study is that of maturation. Maturation is the biological and psychological processes that naturally occur within an individual and could produce changes in the outcome (Campbell & Stanley). Physiological effects, such as hunger or fatigue, could influence testing results. In the current study, all attempts were made to compensate for potential maturation effects within the TBI sample. As it is likely that TBI participants fatigue quicker than their same age peers, multiple breaks were given during testing to alleviate the impact of fatigue.

External validity is the extent to which the results of a study can be generalized to similar populations or across environments (Cozby, 1997). Given that the clinical group for the present study was obtained through a specialty care facility, the sample was not randomly selected. As a result, the findings of this study may not be generalizable outside of the clinical setting or to other children who have experienced a minor brain injury. Another potential threat to external validity includes reactive effects due to testing. The effects of the testing were lessened due to the fact that the TBI patients were not aware during the assessment that the results could potentially be used for a future study.

Summary

The purpose of this study was to investigate the potential differences in executive functioning between children and adolescents with and without a TBI on the CTMT (Reynolds, 2002). According to Reynolds, the CTMT is "highly sensitive to damage, dysfunction, or loss of integrity of the higher cognitive processes of the brain" (p. v). The CTMT purportedly taps into executive control in the areas of selective and divided attention, mental set-shifting, inhibition of responses, and sequencing abilities. The primary research questions in the current study examined whether there were differences between the control and clinical groups on the CTMT Composite Index, as well as on the individual Trails 1 through 5. Outcomes were analyzed using ANOVAs to compare group mean differences between the clinical and control groups on the CTMT Composite Index. A repeated measures MANOVA was utilized to test the hypotheses, which examined whether there were differences between the groups on each individual trail, as well as on groupings of trails (i.e., Trails 1 through 3, and on Trails 4 and 5 combined). A second repeated measures MANOVA was used to test within-group differences on the combination of Trails 1-3 vs. the combination of Trails 4-5 within the TBI group and within the control group. The final research question examined the two factor model of the CTMT standardization sample with a TBI cohort. Analyses were conducted with the TBI group to confirm or refute the two factor model and procedures were repeated with the matched control group to parcel out the possible effects of sample size.

The information obtained for the clinical TBI sample was collected from neuropsychological testing completed at Our Children's House at Baylor. The control sample was obtained from the normative sample of the CTMT, and randomly matched for age and gender with the clinical group. Results of the neuropsychological testing were entered into a database with multiple validity checks to ensure accuracy of entry. Within the present study, all attempts were made to account for potential internal and external threats to validity. Results provide additional insights into the executive functioning abilities of children who have experienced a TBI and lend to the development of appropriate, individualized intervention strategies.

CHAPTER IV

RESULTS

Descriptive Information

This chapter includes the results of the statistical analyses conducted for the current investigation. The participants in this study totaled 160 individuals with 80 being children and adolescents who had sustained a traumatic brain injury and 80 with no known history of head trauma. There were a total of 116 males and 44 females with the clinical and control groups each containing 58 males and 22 females respectively. Of the 160 participants, 60% were Caucasian ($n = 96$), 17.5% were African-American ($n = 28$), 13.1% were Hispanic American ($n = 21$), 1.3% were Asian American ($n = 2$), and 1.3% were Native American ($n = 2$). Ethnicity was missing from 6.8% of the cases ($n = 11$) for the overall sample.

Those participants included in the TBI clinical sample varied in regards to the cause of the head injury. Thirty-five of the participants had been involved in a motor vehicle accident, and 11 were injured due to being hit by a car. Six participants in the clinical group sustained injuries due to a gunshot wound, and 10 sustained injuries due to a fall. Within the TBI group, 11 were injured in an accident with a four-wheeled vehicle and one was involved in a skiing accident. The remaining six participants sustained injuries due to other incidents. Of those who had been in a motor vehicle accident, 15 were not restrained by a seatbelt. The average time between the injury and the neuropsychological evaluation was 20 months with a range of 5 months to 115 months and a median of 11 months. Of the 80 participants in the clinical group, 73 incurred a closed head injury and 7 had sustained from an open head injury.

Comparison Between the TBI and Control Group on the CTMT Composite Index: Hypothesis One

The first analysis examined the potential difference between the clinical group and the control group on the CTMT Composite Index. The Composite Index for each group was attained through summing the *T*-scores of each individual trail and obtaining the overall composite *T*-score from the CTMT manual (Reynolds, 2002). These Composite Index scores for the clinical and control groups were compared using a univariate ANOVA to determine whether a significant difference was present between the groups. An alpha of .05 was selected as the level of significance. The findings for the ANOVA are represented in Table 3. The homogeneity of variances for the ANOVA was tested using the Levene Statistic. This measure tests the assumption that each group of independent variables has the same variance. The stated null hypotheses and results are presented below.

It was hypothesized that no statistically significant difference would be observed between the TBI group and the control group on the CTMT Composite Index. Results of the univariate ANOVA indicated a significant difference when comparing the clinical group and the control group on the overall composite score.

Table 3

Univariate F and Means (SD) of the Control and Clinical Groups on the CTMT Composite Index

				Univariate	
	N	Mean	*SD*	*F*	*p*
CTMT Composite Index				26.52	$\leq .0001$
Control Group	80	45.10	9.14		
Clinical Group	80	36.05	12.79		

Participants who had a traumatic brain injury (*M* = 36.05, *SD* = 12.79) had a significantly lower overall composite score than the non-injured group (*M* = 45.10, *SD* = 9.14), F (1, 158) = 26.52, $p < .0001$, eta^2 = .114. Therefore, the null hypothesis was rejected. The results of the Levene Statistic indicated a significant difference in variances of the two groups (p = .002). The Levene Statistic tests the null hypothesis that the population variances are equal. Given that the results of the current procedure yielded a resulting p-value less than the critical value of .05, the null hypothesis of equal variances is rejected and it is concluded that there is a difference between the variances in the population.

Comparison Between the TBI and Control Group on Each CTMT Trail

A repeated measures MANOVA was utilized to examine the differences between groups on each trail. This analysis was chosen to determine the presence of any main effects or interaction effects between groups on the multiple dependent variables. The dependent variables were comprised of each CTMT trail. Table 4 shows the means and standard deviations of each trail for both the control and the clinical group. In comparing the control and the clinical sample on each individual trail, significant differences were evident across all five trails. The results of the Levene Statistic indicated that no significant differences were observed in the variances of the two groups on all trails. Results of the Levene's test of homogeneity of variance are presented in Table 5.

Hypothesis Two

The stated null hypothesis was as follows: No statistically significant difference will be observed between the TBI group and the control group on the CTMT Trail 1. A significant difference was found when comparing the TBI group versus the control group on the CTMT Trail 1, $F(1, 158) = 13.87, p < .0001$, eta$^2 = .081$. Therefore, the null hypothesis was rejected. These results indicate that there is a significant difference between the clinical group and the control group on the CTMT Trail 1 measuring sequencing abilities. Those participants in the TBI group scored significantly lower than the matched control group. A significant difference was observed in the variances between the TBI group and the control group ($p < .05$). Given the sample size and that the groups were equal, the procedure is considered robust to this violation of the homogeneity assumption.

Hypothesis Three

It was hypothesized that no statistically significant difference would be observed between the TBI group and the control group on each individual CTMT Trail 2. A significant difference was found when comparing the TBI group versus the control group on the CTMT Trail 2, $F(1, 158) = 21.99, p < .0001$, eta$^2 = .122$. Therefore, the null hypothesis was rejected. These results demonstrate that those who have sustained a TBI score significantly lower than control participants on the CTMT Trail 2. A significant difference was observed in the variances between the clinical and control groups ($p < .05$). This resulted in a rejection of the null hypothesis of equal variances and the conclusion that there is a difference between the variances in the population.

Table 4

Means and SDs of the Clinical and Control Groups on Each Individual CTMT Trail

	Control Group (n = 80)		Clinical Group (n = 80)		Univariate
	Mean	SD	Mean	SD	F
CTMT Trail 1	45.09	11.15	37.45	14.57	13.87*
CTMT Trail 2	46.93	11.19	37.43	14.24	21.99*
CTMT Trail 3	46.14	11.32	37.39	13.189	20.28*
CTMT Trail 4	45.96	11.53	37.08	14.341	18.66*
CTMT Trail 5	47.00	8.34	38.34	11.69	29.09*

Note: *All F values significant at the $p < .0001$ level. Means are from a Repeated Measures MANOVA. No significant main effect of trail, $F(4, 155) = .974, p = .424$. No significant interaction of group and trail, $F(4, 155) = .357, p = .839$. A significant effect of control was demonstrated, $F(1, 158) = 29.306, p < .0001$.

Table 5

Test of Homogeneity of Variances for Control and Clinical Group Comparison for Each Individual CTMT Trail

	Levene Statistic	DF	Significance
CTMT Trail 1	5.22	1, 158	.024
CTMT Trail 2	4.25	1, 158	.041
CTMT Trail 3	3.45	1, 158	.065
CTMT Trail 4	5.21	1, 158	.024
CTMT Trail 5	7.48	1, 158	.007

Hypothesis Four

It was hypothesized that no statistically significant difference would be observed between the TBI group and the control group on each individual CTMT Trail 3. A significant difference was found when comparing the TBI group versus the control group on the CTMT Trail 3, $F(1, 158) = 20.28, p < .0001$, eta$^2 = .114$. The null hypothesis was rejected. This demonstrates that the control group performs better on the CTMT Trail 3 than children who have sustained a head trauma. The results of the Levene Statistic noted no significant difference in variances between the two groups ($p = .065$).

Hypothesis Five

It was hypothesized that no statistically significant difference would be observed between the TBI group and the control group on each individual CTMT Trail 4. With regard to the CTMT Trail 4, a significant difference was demonstrated when comparing the clinical versus the control groups, $F(1, 158) = 18.66, p < .0001$, eta$^2 = .106$, resulting in a rejection of the null hypothesis. These results revealed that the TBI group performed significantly lower than control participants on tasks that require set-shifting and cognitive flexibility such as those measured in the CTMT Trail 4. A significant difference was observed in the variances between the groups ($p < .05$) indicating a rejection in the null hypothesis of equal variances.

Hypothesis Six

It was hypothesized that no statistically significant difference would be observed between the TBI group and the control group on each individual CTMT Trail 5. On the

CTMT Trail 5, a significant difference was noted between the clinical and the control groups, $F(1, 158) = 29.09, p < .0001$, $eta^2 = .156$, which leads to a rejection of the null hypothesis. This demonstrates that the TBI group performed significantly poorer on the Trails 5 task which requires switching between letter and number sequences. A significant difference was observed in the variances between the groups ($p < .01$). This is likely due to the standard deviation differences between the clinical and control groups. The control group consistently scored higher on the overall means with a tighter range and less variability within their scores with an average standard deviation of 9.14. Whereas the clinical group demonstrated lower overall means yet greater variability with an average standard deviation of 12.79. This difference is particularly evident on the CTMT Trails 5 comparison due to it being the highest score yet with the smallest range of variability between scores. This is also evident in the overall measure of homogeneity of variance when using a Box's M procedure. A significant difference in the covariance matrices of the dependent variables (i.e., CTMT Trails 1-5) was demonstrated, $F(15, 100512) = 1.92, p = .017$.

Comparison Between the TBI and Control Group on Groupings of CTMT Trails

For these analyses, a repeated measures MANOVA was used due to the multiple dependent variables involved. The means of Trails 1-3 and Trails 4-5 were computed for the clinical and control group, and are presented in Table 6. Tests of homogeneity of variance were conducted for each analysis using the Box's M test, which measures whether the observed covariance matrices of the dependent variables were equal across groups. The null hypotheses and results are presented below.

Hypothesis Seven

It was hypothesized that no statistically significant difference would be observed between the TBI group versus the control group on the CTMT Trails 1 through 3. When the CTMT Trails 1-3 was considered as a set, significant differences were observed between the clinical and control groups, $F(1, 158) = 23.57, p < .0001$, eta^2 =.130. Therefore, the null hypothesis was rejected. This demonstrated that the control group consistently scored higher on the CTMT Trails 1 through 3, which measured simple sequencing abilities.

Hypothesis Eight

It was hypothesized that no statistically significant difference would be observed between the TBI group versus the control group on the CTMT Trails 4 through 5. By combining the CTMT Trails 4-5 together and comparing the means between the groups, significant differences were found, $F(1, 158) = 28.57, p < .0001$, eta^2 = .153, resulting in a rejection of the null hypothesis. This illustrates the differences between groups on the combination of CTMT Trails 4-5 which purportedly taps into executive functioning skills such as set-shifting and cognitive flexibility. The homogeneity of variances was measured using a Box's M test. The results indicated a significant difference in the covariance matrices derived from the combination of CTMT Trails 1-3 and Trails 4-5, *F*

(3, 4493520) = 5.16, $p < .001$. However, MANOVA is considered robust to this violation given the equal samples and number of participants in the current analysis.

Hypothesis Nine

It was hypothesized that no statistically significant difference would be observed within the TBI group on the CTMT Trails 1-3 vs. Trails 4-5. When comparing the two groupings of trails within the clinical group, no significant differences were noted, $F(1, 79) = .122$, $p = .728$, $\text{eta}^2 = .002$. These results show that within the TBI group, scores did not differ between the trails that measure sequencing versus the trails that require set-shifting and cognitive flexibility.

Hypothesis Ten

It was hypothesized that no statistically significant difference would be observed within the control group on the CTMT Trails 1-3 vs. Trails 4-5. Within the control sample, no significant differences were observed between the CTMT Trails 1-3 and Trails 4-5, $F(1, 79) = .188$, $p = .666$, $\text{eta}^2 = .002$. This provides evidence that the scores did not considerably differ between the trails that required simple sequencing abilities and those trails that tapped into higher-order executive functioning skills.

Table 6

Univariate F and Means (SD) of the Control and Clinical Groups on the CTMT Groupings of Trails

	Mean	*SD*	Univariate *F*	*p*
CTMT Groupings of Trails				
Trails 1-3			23.58	$\leq .0001$
Control Group	46.05	9.51		
Clinical Group	37.42	12.73		
Trail 4-5			28.57	$\leq .0001$
Control Group	46.48	8.56		
Clinical Group	37.71	11.93		

Comparison of the Factor Structure of the TBI Group and the Control Group: Hypothesis Eleven

The final analyses examined the latent factor structure within the TBI group and within the matched control group. Analysis of the entire CTMT standardization sample revealed a two-factor model. Factor One consisted of Trails 1-3 and was termed "Simple Sequencing." Factor Two was comprised of Trails 4-5 and was designated as "Complex Sequencing." Analysis was conducted to confirm the findings reported for the standardization sample and to determine if a similar factor model was evident within the clinical group. The stated hypothesis and results are presented below.

It was hypothesized that analysis of the TBI group results would reveal two distinct factors comprised of Trails 1-3 and Trails 4-5. Results revealed a single factor solution. Therefore, the stated hypothesis was rejected. Table 7 displays the factor loading of each trail as evidenced through the through the principal component analysis. The single component solution accounted for 76.35% of the overall variance. A forced factor analysis revealed that a two factor solution accounted for only 9% more variance (84.85%). By adding a second component, the total variance accounted for was not significantly increased; therefore a single factor solution was a better fit for the present sample of TBI participants.

An additional analysis was conducted which examined the latent factor structure within the matched control group. As previously stated, analysis of the entire CTMT standardization sample yielded a two factor model. This final analysis was conducted to determine if the matched control sample would yield a one factor model, as was evident in the TBI group, or a two factor structure similar to the CTMT standardization sample. Table 8 displays the factor loadings of each trail for the principal component analysis. The single component solution accounted for 62.97% of the overall variance. A forced factor analysis revealed that a two factor solution accounted for 14% more variance (76.82%). By adding a second component, the total variance accounted for was significantly increased; therefore a two factor solution is a better fit for the present sample of control participants.

Table 7

Principal Component Analysis of the TBI Sample

CTMT Trails	Single Component Factor
Trail 1	.85
Trail 2	.89
Trail 3	.91
Trail 4	.87
Trail 5	.85
Percentage of Variance	76.35

Table 8

Principal Component Analysis of the Control Sample

CTMT Trails	Component Factors	
	Factor 1	Factor 2
Trail 1	.82	.27
Trail 2	.84	.29
Trail 3	.79	.30
Trail 4	.35	.82
Trail 5	.25	.88
Percent of Variance	62.97	13.87
Cumulative Percentage	62.97	76.82

CHAPTER V

DISCUSSION

The cognitive and behavioral sequelae that result from a TBI often lead to long-term detrimental effects. The National Center for Injury Control and Prevention approximates that each year an estimated 80,000 to 90,000 individuals have a permanent, life-long disability as the result of sustaining a TBI (Langlois et al., 2006). A child may return to school and an adult to the workplace with no visible effects of an injury. However, all too often underlying deficits remain to cause difficulties. Others may not understand the differences in personality or the lack of organized behavior that may become evident as the injured individual attempts to return to "normal" life. Additional emotional struggles may arise as head injured individuals often remember what they were like before the incident and are frustrated with the current lack of functioning.

In children and adolescents, TBIs are the leading cause of death and disability (Jankowitz & Adelson, 2006). Of those that sought medical help, the leading causes of TBIs were falls, motor-vehicle accidents, and assaults. Children who are 14-years-old and younger experience an average of 475,000 brain injuries every year. In young children, falls account for the highest percentage of TBIs, while among older adolescents motor vehicle accidents cause the largest number of TBI related injuries (Langlois et al., 2006).

The consequences of a pediatric TBI often persist throughout an individual's lifetime. Deficits are usually evidenced through memory difficulties, cognitive insufficiencies, attentional issues, and executive dysfunction. Despite the prevalence and long-term detrimental effects, few studies have specifically addressed the executive functioning deficits in a pediatric TBI population using a standardized measure designed to account for the interaction of age and development. To this end, the present study was conducted to compare the executive functioning skills of children and adolescents who have sustained a TBI to non-injured controls using the CTMT (Reynolds, 2002).

The literature reviewed as part of the current study demonstrated the need for measures specifically designed for children. Until recently, with the addition of standardized assessment batteries for children, practitioners routinely utilized tests designed for adults and modified the presentation to make it appropriate for children (Brocki & Bohlin, 2004). This led to the use of non-standardized procedures with poor reliabilities and validity for use with children. With the addition of the NEPSY-II (Korkman et al., 2007), and the D-KEFS (Delis et al., 2001), more appropriate batteries have been created which factor in the effects of age and developmental trajectories when evaluating children and adolescents. The CTMT was also designed to account for these developmental influences. Children and adolescents were included in the standardization sample. The results of those children between the ages of eleven and nineteen were converted to age-corrected scores. The CTMT was based on the original Trail Making Test (Reitan, 1971), yet the CTMT is comprised of five trails instead of two. These additional trails allow for greater specificity in determining areas of deficit. Various trails measures have a long history of demonstrating sensitivity to brain insults and executive functioning deficits such as visual spatial skills, planning, sequencing, and cognitive flexibility or switching (Boll et al., 1977; Jaffe et al., 1993; Reitan, 1955, 1971).

Applications of the Results

The results of the current study provide additional support for trails measures being reliable in differentiating those individuals who have sustained a head trauma compared to their non-injured peers. The Armstrong, Allen, Donohue, and Mayfield (in press) research demonstrated that the TBI sample evidenced scores approximately 2 standard deviations below the control sample mean on all five of the CTMT trails, as well as on the Composite Index. Using a control sample which was matched on age, gender, ethnicity, and geographic location, Armstrong and colleagues reported significant differences between the groups at the $p < .001$ level. The current investigation confirmed these results. Utilizing a larger sample than the previous study, results remained significant when comparing the TBI group and control group on the overall CTMT composite score. Significance was seen at the $p < .0001$ level with the TBI group scoring notably lower than the control group. When the CTMT trails measures were separated into individual trails, significant differences were noted between groups at the $p < .0001$ level. When comparing the means and standard deviations of each trail between groups, the control group scored significantly higher and had smaller standard deviations. This indicated that there were overall lower scores on each trail (i.e., longer completion times) and more variability between those scores within the clinical group. Overall, the current study verified the previous researchers' findings indicating significantly lower scores for the TBI group in all areas of the CTMT. This supports the conclusion that the CTMT demonstrates strong sensitivity and good overall utility for use with the TBI population.

One important difference between the clinical and control groups was the standard deviations (SD) of each individual trails. The overall mean SD for the five trails for the control group was 9.14, whereas the average SD for the clinical group was 12.79. It is likely that the lower overall mean scores and increased variability within the TBI group is due to the nature of the disability. As was previously discussed in the literature review, individuals who sustain a TBI often display a scatter of abilities and deficits depending on various external factors. External variables such as age at injury, location and severity of injury, as well as the time of recovery since the injury (e.g., Farmer et al., 1997; Slomine et al., 2002; Ylvisaker & DeBonis, 2000) could have had an effect on the reported results.

When the CTMT trails measures were combined into groupings of Trails 1-3 and Trails 4-5, significant differences were noted between the clinical and control groups. However, when examining within group differences, no significance was demonstrated between the clinical and control samples on the combined mean of Trails 1-3 and Trails 4-5. Despite the added executive control necessary to respond to the task-switching demands of Trails 4-5, no significant differences were evidenced within the control group or within the TBI group. The mean scores were slightly higher on Trails 4-5 versus Trails 1-3 for each group but not to a level of significance.

The current investigation also attempted to confirm the two-factor model that was reported in the CTMT standardization sample with a group of TBI participants. It was hypothesized that the two factor model would also be present in the TBI group; however, this was not evidenced by the data. The analysis revealed that a single component solution accounted for 76% of the overall variance. A forced factor analysis revealed that a two factor solution accounted for only 9% more variance. By adding this second component the total variance accounted for did not significantly increase. These results demonstrate that a single factor solution was the best fit for the current TBI sample. This primary factor is likely due to the similarity between each trail measure. While Trails 4-5 increases the demand on executive functioning due to the switching component, all five of the CTMT trails tap into planning abilities, sequencing, speed of processing, and visual scanning. It is likely that these primary abilities are loading onto the principal factor seen in the analysis.

It is also possible that the differences seen between the one-factor results of the current study, versus the two-factor model in the standardization sample, could likely be a function of the differing sample size. The eighty participants used for the current analysis is on the low end of the recommended sample size for a confirmatory procedure. The same analysis was repeated using the matched sample control group to determine if the data would reveal a single component structure, as in the TBI sample, or a two-factor solution evidenced in the entire CTMT standardization sample. Results demonstrated that a single component accounted for 63% of the overall variance. When adding an additional factor 14% more of the overall variance was accounted for with a two-factor solution. Factors are considered "pure" when the items load onto a component at .45 or higher, and are below .33 on other factors. As can be seen in the current analysis, factor one has loadings above that level for Trail 1 (.82), Trail 2 (.84), and Trail 3 (.79). Factor two is comprised of Trail 4 (.80) and Trail 5 (.88). These high loadings demonstrate that a two-factor model is a better fit for the matched sample control group. This result coincides with the factor structure evidenced in the CTMT standardization sample.

Another potential cause for the differing results could be the basal and ceiling effects of the test measure used. On the CTMT the lowest possible *T*-score that an individual could obtain could be 17. However, six individuals had results indicating scores below this basal point. While this hindrance likely did not affect the results of the comparisons between the clinical and control groups, it may have influenced the comparisons within the TBI group. Greater differences between the groupings of Trails 1-3 versus Trails 4-5 in the clinical sample may have been evident if a lower basal was possible with the CTMT.

Implications for Intervention

After a TBI executive functioning deficits can significantly impact several key areas of cognitive, behavioral, or social functioning. Attempting to rehabilitate a loss of executive functioning has been described as challenging and "enigmatic" (Cicerone, 2002, p. 246). While deficits in other areas (i.e., motor skills or language) require direct instruction of a specific skill, remediating executive skills demands reliance on underlying knowledge and application of the skill. This often requires the individual to not only learn the appropriate behavior but also the ability to apply that action in novel situations and self-monitor the effects of that act (Cicerone).

This process of rehabilitating executive functioning in the areas of self-regulation, organization of complex behavioral sequences, and the coordination of mental thought processes, is daunting to say the least. Before intervention can began, a theoretical framework for conceptualizing the strategies needs to be in place. One such model discussed previously in this review, was explained by Norman and Shallice (1986) as the supervisory control system. This supervisory system categorizes the organization of cognitive and behavioral processes into schemas. These schemas represent over-learned routines that are monitored on a basic level through contention scheduling (Norman & Shallice). The secondary, more complex level involves the supervisory executive system. This monitors the implementation of the behavioral sequences through responses to novel situations (Cicerone, 2002). This monitoring occurs when the habitual responses need to be inhibited given the situation, or when the appropriate responses have yet to be learned.

Deficits in the supervisory control system after a TBI would be evident through poor problem-solving abilities, difficulties inhibiting learned responses, and failing to respond to error correction. All of these skill deficits are assessed on executive functioning measures such as the CTMT. The CTMT taps into the inhibition of habitual responses by requiring cognitive flexibility between sequences of letters and numbers. Those with control system deficits struggle to inhibit the over-learned sequences of 1-2-3 and A-B-C and switch between the letter and number series (i.e., A-1-B-2, etc.). Responses to error correction are also measured on the CTMT. When an individual makes a mistake in the sequence, the examiner is required to correct the error immediately and the task is picked up where the error took place. Failing to respond to the error correction will lead to a longer completion time and thus a lower score. This response to error correction requires executive control by being able to learn from environmental cues and regulate one's behavior. The CTMT would be helpful in identifying these possible supervisory control system deficits.

Once the executive control difficulties have been determined, possible intervention strategies can be developed to address these deficits. In order to elicit positive changes in the supervisory control system, one possible intervention strategy that has proved effective involves a self-instructional training procedure (Cicerone, 2002). This was designed to teach injured individuals how to plan ahead and self-monitor behaviors. Using the Tower of London task (Shallice, 1982), the individuals were required to verbally state the moves before and during the completion of the task. Next, the individuals were expected to repeat the process but instead of verbalizing the moves, they were instructed to whisper under their breath. Lastly, they repeated the task while using internal talk rather than expressive, audible speech (Cicerone, 2002). The number of incorrect moves dropped with each phase and remained consistent across 8 weeks of treatment with no regression evident at 4 months post-treatment (Cicerone). This increased self-monitoring was also generalized to everyday behaviors. The positive outcome of this self-instructional intervention technique demonstrates the importance of retraining self-monitoring and planning abilities. Successful rehabilitation of the supervisory-executive control system after a TBI, would be evident through the individual's increased problem-solving abilities, enhanced ability to modify behavior in unexpected situations, and the capability to inhibit inappropriate responses based on the current situation (Cicerone).

Educational Implications and Interventions

With TBIs being the leading cause of disability in children under 15-years-old, the education system is uniquely available to assist in the rehabilitation process (Semrud-Clikeman, 2001). Depending on the severity of the injury, children typically return to school as soon as they are able. School re-entry is often encouraged as it marks a return to what was "normal" prior to the injury. Unfortunately, all too often educators and school practitioners are inadequately trained to address the diverse needs evidenced in this population. In 1990, traumatic brain injury became a separate disability category in special education law with the passing of Public Law 101-476, which is otherwise known as the Individuals with Disabilities Education Act (IDEA). This federal law guides the provision of special education and related services to children and youth with disabilities in the public school system (Semrud-Clikeman). IDEA defines traumatic brain injury as the following:

> ...an acquired injury to the brain caused by an external physical force, resulting in total or partial functional disability or psychosocial impairment, or both, that

adversely affects a child's educational performance. The term applies to open or closed head injuries resulting in impairments in one or more areas, such as cognition; language; memory; attention; reasoning; abstract thinking; judgment; problem-solving; sensory, perception, and motor abilities; psycho-social behavior; physical functions; information processing; and speech. The term does not apply to brain injuries that are congenital or degenerative, or to brain injuries induced by birth trauma. [(Code of Regulations, Title 34, Section 300.7(b)(12)]

With the addition of this definition into federal law, the onus was placed on the public school system to provide educationally-related academic, behavioral, and language based interventions. As discussed previously in this review, diverse deficits often evident after a TBI may include impairments in memory, attention, language, motor skills, and executive functioning. Given these ubiquitous difficulties the challenges of providing appropriate educational interventions are immense. The first step is to obtain an accurate assessment of where the child is currently functioning within these fundamental areas upon school re-entry. This is where research, such as the current investigation, is vital in determining appropriate measures for use after a pediatric TBI. Standardized broad-based measures (e.g., NEPSY-II) or stand alone assessments (e.g., CTMT), which have proven utility and strong specificity, are appropriate as part of an overall evaluation of the child's functioning post-injury.

This thorough assessment should then be used to drive the development of an individualized education plan and intervention strategies. This plan needs to be flexible and the assessment may need to be frequent as the child will likely display significant progress during the first six months. Gradual recovery may continue after that for several years (Semrud-Clikeman, 2001). Accurate and frequent assessments are also important as new deficits may emerge. Children often "grow" into their deficits as they mature (Ylvisaker & DeBonis, 2000). For example, a 6-year-old who sustains a head injury will not be expected to use complex, abstract thinking skills upon her return to school. However, that frontal lobe damage may persist until middle school when she is required to utilize those higher order thinking skills. Yet, she is unable to do the required tasks due to the history of the TBI. As the brain continues to heal and additional coping mechanisms are learned, appropriate assessments batteries including measures such as the CTMT will be critical for accurately evaluating current progress and in modifying intervention strategies.

Limitations

The current investigation is limited due to the lack of random selection for the clinical group. The TBI sample was obtained from a pediatric specialty care hospital and the individuals were tested during follow-up visits as out-patients. Random sampling is preferred so that each member of the population being examined has an equal likelihood of being selected for the investigation. Given this limitation, the findings of the current study may be unique to this sample and not generalizable to a larger TBI population.

This study is also limited by the type of individuals included in the TBI sample. Due to the selection process from a hospital setting, it is likely that the clinical group sustained moderate to severe head injuries. The lack of inclusion of mild head injured individuals likely resulted in lower overall mean scores on the CTMT trails measures. It is known that a majority of head injuries are mild in nature (Kraus, 1995), yet few of these injured seek medical intervention (Langois et al., 2006). Given this fact, it is probable that no mild head injuries would be seeking intensive rehabilitation and thus would not been included in the clinical group for this investigation.

Another potential limitation is due to the assessment measure chosen to evaluate executive functioning. Given the developmental trajectory of frontal lobe functioning (e.g., Romine & Reynolds, 2005), the youngest age that can be tested with the CTMT is age 11. This age range limited the amount of younger children included within the clinical group. With the mean age of participants being 15-years-old, it is possible that these results would be different with the inclusion of younger children. Yet, as Archibald and Kerns (1999) noted, executive functions are likely to change with maturation and take different forms at different ages. As the maturational course of executive functions transpires, so the test measures used to assess these skills must also adapt. Diamond et al. (2005) demonstrated this fact by showing that task-switching abilities, like those measured on the CTMT, evidenced a distinct developmental course where the younger participants were unable to switch between given conditions. So, despite the limited age range for older children and adolescents on the CTMT, this limitation may also be a strength of the investigation in that the measure more accurately assesses a specific developmental phase of executive functioning.

It is possible that the CTMT outcomes in the current study were influenced by the environmental testing differences between the clinical and control group. The clinical group was tested on the CTMT as part of a larger neuropsychological battery. This likely took considerably longer and was more taxing than the administration of the CTMT alone, which was the case in the normative sample. It is known that individuals who have sustained a TBI often suffer from increased fatigue, poor attention span, and difficulty concentrating (Semrud-Clikeman, 2001). Despite frequent breaks and interventions to control for these influences, it is possible that the results of the TBI sample could have been affected by these factors.

This study may also have been limited by the variability between the time since the injury and the date of testing. While the average length of time was 20 months the range varied between 5 months and 115 months of recovery, with the median number of months being 11. Given that the brain is continuing to recover for up to five years post-injury (Semrud-Clikeman, 2001), this variability of time may have resulted in different outcomes for the clinical group.

Another potential limitation for the current sample was the gender distribution. There were 116 males and 44 females included in this study. While there were considerably more males to females, it is likely this had a minimal impact on the results for two reasons. First of all, in the standardization sample of the CTMT no significant differences were seen between the genders (Reynolds, 2002). Secondly, the statistics on gender distribution for those who sustain a head injury indicates that males are 1.5 times more likely than females to sustain a head injury (Kim, 2006). While the current sample had slightly more than the 1.5 ratio of males to females it is not likely that this significantly impacted the results.

Future Research

It is evident that more research is needed related to the executive functioning of children and adolescents who have sustained a head injury. Given the life-long impact and educational implications of a pediatric TBI, more research is necessary to drive appropriate intervention strategies. The current study could be expounded upon to include those who have had a mild head injury. This would increase the generalizability to a broader TBI population and possibly allow for a better understanding of the impact of severity of injury on executive functioning. The current study could also be expanded to include other measures of executive functioning. Given the discrepancies in defining executive functioning (e.g., Anderson, 1998; Baddeley, 1996; Lezak, 1995; Norman & Shallice, 1980, etc.), various assessment measures likely tap into the differing aspects of executive control. The CTMT primarily measures the executive abilities of planning, visual scanning, processing speed, and set-shifting. Other comprehensive measures of executive functioning or various stand-alone measures may assess abilities outside of the purview of the CTMT and provide different results within the TBI population.

Future studies also need to be completed which utilize the CTMT with other clinical populations. While the CTMT showed strong reliabilities and validity in its development (i.e., Gray, 2006; Moses, 2004; Reynolds, 2002) with an LD population, a gifted subgroup, and a CVA sample, additional external research is needed to validate these results. Two outside studies have supported the CTMT's validity (i.e., Servesko et al., 2006) and its overall utility and specificity (Armstrong et al., in press), yet additional research is needed to confirm these results with other subpopulations.

It would also be beneficial to have additional research related to the interaction effects of development and the time of injury. As was noted in several studies previously reviewed (e.g., Anderson, 2002; Blair et al., 2005; Diamond et al., 2005; Espy et al., 2001; Zelazo et al., 2002), the developmental trajectory of executive functioning exhibits a stair-stepped trajectory. The maturational course varies depending on the specific skill being examined. Brocki and Bohlin (2004) demonstrated this fact by showing that the executive functioning abilities of fluency, disinhibition, and speed/arousal all displayed different developmental trajectories in children aged 6- to 13-years-old. Given the age range of the current study between 11- and 19-years-old, developmental trends were not examined. However, future research should include a wider age range of individuals and use a measure that could accurately tap into the emerging skills at each developmental phase.

Longitudinal research in this area would also be a valuable asset to the current knowledge base. Given the rapid initial improvements that often take place following a TBI, as well as the deficits that may emerge post-injury, long-term studies are needed to chart these changes. Depending on the age when the injury occurred, as well as severity and location of the injury, the cognitive and behavioral sequelae may differ greatly

(Brookshire et al., 2004). A study that includes all of these influential factors over a long period of time will better be able to parcel out the variables that best predict positive and negative outcomes.

Conclusion

Executive functions influence every area of life. Even basic daily living skills, such as cooking a meal or driving a car, involves the integration of complex motor sequences, cognitive flexibility, and planning abilities. All of these actions are mediated through executive control in an integrated network of neurological processes. If any portion of the network is disrupted due to a head injury, a diverse sequelae of cognitive and behavioral deficits may ensue (Luria, 1973). Rehabilitation of these deficits is challenging given the integrated nature of the executive system in both the acquisition of a skill, as well as the application and modification of that behavior in novel situations (Cicerone, 2002). Deficits after a pediatric TBI may significantly impact that child's academic functioning and success in school. With the addition of TBI as a separate disability category in special education law since 1990, the responsibility has been bestowed on the education system to accurately assess the distinct needs of TBI students. This assessment would then drive the implementation of an individualized education plan and appropriate related services to address the deficits. The results of the current study added to the current knowledge base by providing support for the use of the CTMT in the assessment process post-injury.

Results demonstrated that the CTMT reliably discriminated between the TBI group and the matched control group. This was evident through examining the overall composite score as well as differences between each individual trail. Discrepancies were also noted between groups when the trails were combined conceptually based on task demand into Trails 1-3 and Trails 4-5. These results confirm the Armstrong, Allen, Donohue, and Mayfield (in press) research that demonstrated that the CTMT was a valid and specific measure for differentiating those who had sustained a head injury versus non-injured controls.

When examining group differences within the TBI sample or within the control group, no significant differences were evidenced. However, the TBI group did show more variability within their results. This confirms prior research that individuals who sustain a TBI often display a scatter of abilities due to factors such as age at injury, location and severity, as well as time of recovery since injury (e.g., Farmer et al., 1997; Slomine et al., 2002; Ylvisaker & DeBonis, 2000). Attempts to confirm the two factor model reported in the CTMT standardization sample revealed that a single factor solution was a better fit for the present sample of TBI participants. The primary component was able to account for 76.4% of the overall variance and the addition of a second factor did not significantly increase the total variance accounted for. Analysis of the matched sample control demonstrated congruence with the CTMT standardization sample in that a two factor solution was a better fit for data. Additional research is necessary to confirm or refute these results with a larger sample size of TBI participants. Overall, the results of the current investigation demonstrate that the CTMT is appropriate for use with the pediatric TBI population for detecting executive functioning deficits in the areas of sequencing, visual scanning, planning, and cognitive flexibility.

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