COGNITIVE ABILITY PREDICTS PERFORMANCE ON A VIRTUAL REALITY MEASURE

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A thesis submitted in partial fulfillment of
the requirements for the degree of
Master of Arts

Department of Psychology

Central Michigan University
Mount Pleasant, Michigan
November, 2012

Accepted by the Faculty of the College of Graduate Studies,

Central Michigan University, in partial fulfillment of

the requirements for the master's degree

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ACKNOWLEDGEMENTS

I would like to thank several individuals who have supported me with my thesis. First, I would like to thank Dr. Reid Skeel, Thesis Committee Chair, whose patience is commendable. His continued encouragement and insight throughout this process and throughout my graduate experience in general has been invaluable. Dr. Nathan Weed brought to my attention several new ideas and recommendations; I want to thank him for always challenging me and for supporting me and my education as a whole. Without Dr. Ksneia Ustinova, there would be no data for a research project; I would like to thank her for allowing me to be part of her team. Her expertise and guidance in a field other than my own has taught me the importance of collaboration.

In addition, many other individuals contributed to this thesis who deserve to be mentioned. First, several graduate students in Dr. Ustinova's lab, including Amanda Schafer, helped to collect part of the data. Thanks to Dr. Kyunghee Han for going above and beyond in helping me with statistical analyses. This project would not have been possible without their assistance.

Finally, I am grateful for the continued support of my family and friends. My parents taught me to never give up and to be proud of my work; their lesson on persistence came through loud and clear. My family and friends also reminded me that breaks are necessary and laughter is a must; I want to thank them for making this project possible.

ABSTRACT

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VIRTUAL REALITY MEASURE

by Rochelle L. O'Neil

Few studies have examined whether motor learning in individuals with neurological impairment occurs in the same way as in healthy individuals. Although some studies have examined this relationship in individuals with stroke, few studies have been conducted with individuals with a history of traumatic brain injury (TBI). Virtual reality simulations have been utilized in a variety of areas including rehabilitation and neuropsychological assessment, and provide the opportunity to systematically examine motor learning. This study utilized virtual reality simulations to examine general movement and learning in individuals who have a history of TBI. Results showed numerous correlations between overall performance and several of the cognitive ability domains for both the patient and control groups, with correlations generally decreasing from Day 1 to Day 2 as participants learned the task. Overall, cognitive ability level explained a significant amount of variance over and above demographic variables in the total sample. However, rate of learning was not different between groups, which may have been a result of task difficulty; participants might not have been afforded the opportunity to demonstrate learning. The current results may provide a starting point for other virtual reality studies and rehabilitation programs regarding which cognitive domains should be the focus of intervention.

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CHAPTER I

INTRODUCTION

Virtual reality simulations have become an area of interest with regard to therapy and rehabilitation (Cherniak, 2011; Holden, 2005; Mumford & Wilson, 2009). There are several advantages to using these simulations including increased motivation of participants (Holden, 2005; Sveistrup, 2004; Thornton et al., 2005), a safe environment that minimizes risk (Flanagan et al., 2008; Schulteis, Himelstein, & Rizzo, 2002), and an environment that is easily manipulated on an individual level (Rizzo & Kim, 2005; Schultheis et al., 2002). Additionally, it has been argued that the use of virtual simulations increases ecological validity. Typical measures tend to assess one isolated aspect of functioning; however, the real world requires integration of many skills (Matheis et al., 2007). Virtual reality-based assessment allows for inclusion of complex challenges that are naturally found in the real-world, not only increasing relevance of the task itself, but improving predictive validity (Rizzo & Kim, 2005).

Motor Learning and Virtual Reality

One particular area of interest that utilizes virtual reality simulations is that of motor learning, which can be defined as an internal process that results in a relatively permanent change in an individual's capability to perform a motor task (Kerr, 1982; Magill, 2004; Schmidt & Wrisberg, 2004). In 2009, Mumford and Wilson conducted an extensive review of the literature related to virtual reality and acquired brain injury; they found that the majority of research focused almost exclusively on patients with stroke, and that studies which examined patients with TBI were lacking.

Cognitive Functioning and Motor Learning

In order to successfully apply the concepts of motor learning to patients with TBI, it is first necessary to understand how cognitive functioning affects motor learning. Much of the literature has focused on research using dual-task paradigms. This type of design requires participants to complete a number of tasks separately and then simultaneously to examine the change in performance.

Dual-Task Paradigms

Results from a recent meta-analysis demonstrated that when participants engaged in a dual-task paradigm, their performance was slowed, indicating that control of gait requires resources from higher-order systems (Al-Yahya et al., 2011). This effect was prevalent across different populations, including older adults and individuals with neurological disorders, as well as for a variety of cognitive tasks. Overall, the literature regarding dual-task paradigms suggests a variety of causes for the decline in performance: inability of the brain to effectively allocate resources, decrease in cognitive resources available due to injury, and motor and cognitive domains sharing a pool of resources (Catena, van Donkelaar, & Chou, 2007, 2009; Holtzer et al., 2006; Sosnoff, Broglio, & Ferrara, 2008).

Research in Individuals with Stroke

There have been few studies that have examined whether motor learning in individuals with neurological impairment occurs in the same way as in healthy individuals. Winstein, Merians, & Sullivan (1999) examined this concept in 40 patients with stroke (20 with right hemisphere damage and 20 with left hemisphere damage) and 40 healthy individuals. Participants performed a specific motor task while in the seated position. The researchers found that with practice, both groups demonstrated improvement. There were also no differences between groups regarding forgetting and savings, suggesting that the capacity for motor learning remains intact following stroke (Winstein et al., 1999).

In contrast, Cirstea, Ptito, and Levin (2003) investigated whether a group of 20 patients with stroke improved in the same way as 10 healthy controls. Motor impairment was assessed by comparing arm reaching in the two groups. Although results demonstrated improvements for both groups after just one practice session, patients displayed arm movements that were more varied. Researchers also found that the patients with stroke required many more repetitions in order to demonstrate changes comparable to healthy individuals (e.g., 55 versus 20; Cirstea et al., 2003).

The Current Study

Although these studies have demonstrated differential effects within people with stroke, it is unknown whether these results can generalize to people with a history of TBI. Therefore, the current study utilized virtual reality simulations to examine motor learning in individuals who have experienced varying degrees of TBI in order to determine how cognitive deficits caused by brain damage affect the process of motor learning. In other words, do people with brain injuries have the same pattern of learning as healthy individuals, or are there specific components that affect motor learning in individuals with a history of TBI? Specific points of interest were the rate of learning and the overall performance of each participant on the virtual reality task and the relationships between neuropsychological test measures and performance on the virtual reality task.

Hypotheses

It was hypothesized that the control group would demonstrate a higher level of motor performance than the TBI group. It was also hypothesized that both groups would demonstrate learning across trials, but that the control group would learn at a faster rate. Considering the requirements of the virtual reality task itself, it was hypothesized that neuropsychological test measures involving motor abilities, visual memory and visuospatial abilities would be correlated with motor scores from the simulation. The dual-task research has emphasized the importance of executive functions in the allocation of resources; however, it was hypothesized that there would not be a significant association between motor functioning and executive functions because it is unlikely that the virtual reality simulation would be cognitively challenging enough to tax executive functions to produce the effect that a dual-task paradigm yields.

CHAPTER II

METHOD

Participants and Design

Participants included an experimental group that consisted of 15 individuals with a history of TBI, and a control group that consisted of 15 healthy individuals. The 15 participants of the experimental group were recruited through a variety of sources including advertisements in local newspapers and newsletters as well as advertising during TBI support groups in the community and word of mouth (i.e. many participants knew of others who may be interested and took a flier for them). Experimental participants underwent an initial screening; these participants were required to have sustained some type of head injury, have problems with balance and coordination (but be able stand independently for at least a two-minute period), and to be able to see clearly in front of them in order to see the screen for the virtual reality simulation. However, after initial analyses, one patient was dropped from the sample due to being an outlier on both age and education. Therefore, the final analyses included a total of 14 patients.

The control group consisted of a convenience sample that was recruited from university staff and students. Although an additional control participant could have been dropped from analyses for group equivalence, all 15 control participants remained in analyses in order to preserve the sample size. Each group completed both the virtual reality simulation and the neuropsychological testing. All participants were informed that the information they provided throughout the course of the experiment would be de-identified through the use of subject numbers, and that the videotaped portion of testing would be destroyed following completion of the study.

Materials

Virtual Reality Simulation

The virtual reality simulation was powered through the use of a Dell Mobile Precision M6500 laptop equipped with a graphics accelerator as well as six cameras designed for motion capture. The images appeared on an 82-inch television screen with three dimensional first-person view made possible through RealD shutter glasses worn by participants. Each participant wore three markers attached to each hand that were integrated with the images projected onto the television screen.

The virtual reality simulation provided information regarding participants' motor skills and learning. Participants were introduced to an underwater environment that included seaweed and coral landscape. In addition, an octopus was positioned in the center of the screen and blew bubbles in the direction of the participant. The objective of the simulation was to pop as many of the bubbles as possible by reaching out with the left or right hand; each bubble popped earned participants points. On each occasion, ten 90-second trials were completed, yielding a performance score (total number of points) for each trial. If participants were performing well (popping the bubbles right away), the rate at which the bubbles appeared increased, allowing for the opportunity to pop more bubbles and earn more points in the 90-second period. There was no limit to the number of bubbles that could be presented during these trials. Overall, scores included a measure of initial performance, calculation of each participant's learning slope, and a measure of retention.

Neuropsychological Testing

The following materials, organized by domain, were utilized for the neuropsychological testing.

Verbal Memory. *California Verbal Learning Test – Second Edition* (CVLT-II; Delis, Kramer, Kaplan, & Ober, 2000). The CVLT-II is a test of verbal memory. Participants were read a list of words and were required to recall as many of the words as possible, in any order. This process was repeated for five trials, and each trial provided a raw score and standard score. The participants were then provided a cued recall trial in which they were given specific categories describing the words to be recalled. Raw scores (the number of words recalled for a specific trial) and scaled scores (based on raw scores and age of participant) are reported for each of the five immediate recall trials as well as a total raw and standard score for the five trials combined. Standard scores are reported as z-scores. After these immediate recall trials, a second, novel list of words was read to the participant and s/he recalled as many of the words from this novel list as possible. After this short delay, the participant was again asked to recall as many of the words from the first list as possible as well as a cued recall trial, without being read the list an additional time. After a 20-minute delay, participants were again asked to recall as many of the words from the first list as possible along with a cued recall trial. Finally, participants were read a number of words and were required to say "yes" if the word was on the first list or "no" if the list was not from the first list. The CVLT provides raw scores and standard scores for the immediate recall trial, short delay, and long delay trials for both free recall and cued recall sections.

Internal consistency has been measured using three methods: two split-half approaches and one examination of alpha values. Across the three methods, internal consistency coefficients ranged from .79 to .94, indicating high internal consistency for the immediate recall trials. Based on 78 people, test-retest reliability statistics were calculated over a median 21-day period (range 9-49 days) for a variety of indices including both overall achievement indices and process-oriented indices. Overall achievement indices demonstrated high test-retest reliability (range .80 to .89); however, process-oriented indices had poor test-retest reliability (<.59), indicating that caution should be used when attempting to interpret variables related to the participants' learning strategies (Strauss, Sherman, & Spreen, 2006).

Visual Memory. *Wechsler Memory Scale – Fourth Edition: Visual Reproduction I and II (*WMS-IV: VR-I, VR-II; Wechsler, 2009a). Visual Reproduction (VR) is part of the WMS-IV and consists of three portions: VR-I, VR-II, and a recognition portion designed to measure visual memory. Scores for VR-I and VR-II are based on a scoring rubric for each of the five designs. VR-II is administered 20-30 minutes after VR-I. Scoring criteria are based on specific components of each design scored as 0 or 1 (0-43 total points possible). Scaled scores (range 1-19) are based on the raw scores and depend on the age of the participant. Immediately following VR-II, the recognition section is administered which yields a raw score (0-7 points) and a cumulative percentage. VR-I has an overall average internal consistency of .93, and the overall average internal consistency for VR-II was .96. Based on 244 adults, test-retest reliability statistics were calculated over a 23 day period (range 14 to 84). 173 adults completed the adult battery and 71 completed the older adult battery. For VR-I, the overall test-retest reliability was .62; however, corrected for variability in the sample, the correlation increased to .67. Likewise, the uncorrected test-retest reliability for VR-II was .59, and the corrected correlation was .64 (Wechsler, 2009b).

Processing Speed. *Symbol Digit Modalities Test* (SDMT; Smith, 1991). The SDMT is a measure of processing speed that can be administered either in written form or oral form. Participants were required to convert geometric symbols into either written or oral responses depending on the form used. If both forms are administered, as in the current case, the written version is administered first followed by the oral version. A single z-score is provided for both the written and oral forms. A negative z-score indicates that the participant's performance is worse than average, whereas a positive z-score indicates above average performance on the task. Based on 80 adults, the SDMT demonstrates fairly stable scores (across 29 days), with a test-retest reliability of .80 for the written version and .76 for the oral version (Smith, 2010).

Trails 1, 2, and 3 from the Delis-Kaplan Executive Function System (D-KEFS Trails; Delis, Kaplan, & Kramer, 2001a). D-KEFS Trails measures a variety of domains. The first three conditions are measures of processing speed: Visual Scanning (Trails 1), Number Sequencing (Trails 2), and Letter Sequencing (Trails 3). These conditions involve visual cancellation or require participants to connect the dots, sequencing numbers or letters. The scaled scores are calculated based on the time (in seconds) to complete the task. Scaled scores (range 1-19) depend on the person's age, with a higher score corresponding to better performance.

Reliability statistics were separated by age group. The internal consistency of D-KEFS Trails ranged from .57 (10 year olds) to .81 (50-59 year olds), indicating moderate to high internal consistency. Based on 101 people, test-retest reliability statistics were calculated over a 25 day period (range 9 to 74). Across the three processing speed conditions, test-retest reliability ranged from .56 (Condition 1: Visual Scanning) to .59 (Condition 2: Number Sequencing and

Condition 3: Letter Sequencing) indicating moderate test-retest reliability (Delis, Kaplan, & Kramer, 2001c).

Basic color naming and word reading from the Delis-Kaplan Executive Function System (D-KEFS Color-Word Interference Test; Delis et al., 2001a). The Color-Word Interference Test consists of three total conditions. The first two conditions measure processing speed: Basic Color Naming and Word Reading.

Reliability statistics were separated by age group. The internal consistency of the D-KEFS Color-Word Interference Test ranged from .62 (13 year olds) to .86 (50-59 year olds), indicating moderate to high internal consistency. Based on 101 people, test-retest reliability statistics were calculated over a 25-day period (range 9 to 74). The first condition, Color Naming, had a test-retest reliability of .76, and the second condition, Word Reading, had a test-retest reliability of .62 (Delis et al., 2001c).

Executive Functioning. *Trails 4 from the Delis-Kaplan Executive Function System* (D-KEFS Trails; Delis, Kaplan, & Kramer, 2001a). The fourth condition in the D-KEFS Trails test is Number-Letter Switching, a measure of executive functioning; this task required the participant to connect the dots, switching between numbers and letters. Number-Letter Switching (Trails 4) is the primary visual-motor sequencing task because it measures flexibility in thinking (Delis, Kaplan, & Kramer, 2001b). Test-retest reliability for the Switching condition was .38 (Delis et al., 2001c).

Inhibition from the Delis-Kaplan Executive Function System (D-KEFS Color-Word; Delis et al., 2001a). The third condition of the Color-Word Interference Test, Inhibition, is a measure of executive functioning centered on the concept of inhibition of a more automatic response in order to produce a conflicting response. This condition measures not only verbal inhibition, but simultaneous processing and cognitive flexibility as well. Raw scores reflect completion time for each condition (in seconds) and are converted into scaled scores (range 1-19) based on the person's age (Delis et al., 2001b). Test-retest reliability for the Inhibition condition was .75 (Delis et al., 2001c).

Controlled Oral Word Association Test (COWAT; Benton & Hamsher, 1976). The COWAT is a test of executive functioning consisting of two sections. The first involved saying aloud words beginning with specific letters of the alphabet. (Ex: Say aloud as many words as you can think of starting with "F"). These directions are repeated for the letters "A" and "S". The second section involved saying aloud words that were animals. Two z-scores were reported, one for the combined number of words named based on the three phonological cues, and one for the total number of animals. A negative z-score indicated that the participant's performance was worse than average, whereas a positive z-score indicated above average performance on the task. Inter-rater reliability was described as nearly perfect by Spreen and Strauss (1998). Test-retest reliability calculated across a 19-42-day period was .88 (des Rosier & Kavanaugh, 1987). Additionally, Dikmen, Heaton, Grant, & Temkin (1999) tested a group of 81 friend and trauma controls and found test-retest reliability to be .72. Both studies represent good test-retest reliability statistics for the COWAT.

Motor Functioning. *Trails 5 from the Delis-Kaplan Executive Function System* (D-KEFS Trails; Delis, Kaplan, & Kramer, 2001a). The final condition of the D-KEFS trails test is Motor Speed (Trails 5), and required the participant to trace over a dotted line as quickly as possible. This condition helps to ensure that a poor score on the other four conditions is not due to motor functioning. Test-retest reliability for Motor Speed was .77, indicating a high test-retest reliability (Delis et al., 2001c).

Grooved Pegboard Test (Kløve, 1963). The Grooved Pegboard Test is a measure of motor functioning consisting of a pegboard with a total of 25 holes arranged in a 5x5 grid; the pegs themselves and the holes in the pegboard have a side that is square and a side that is round. Participants were required to put the pegs into the board as quickly as possible, using only one hand and completing the rows one after the other, in order (Lezak, Howieson, & Loring, 2004). Two z-scores were reported based on completion time (in seconds), one for the dominant hand and one for the non-dominant hand. A negative z-score indicated that the participant's performance was worse than average, whereas a positive z-score indicated above average performance on the task. Test-retest reliability was based on a sample of 121 individuals comprised of mixed normal controls (no history of brain disease or trauma) over a 2-12-month period. The reliability coefficient was .86 for both the dominant and non-dominant hand, indicating good test-retest reliability over time (Dikmen et al., 1999).

Finger Tapping Test (Halstead, 1947). The Finger Tapping Test is another measure of motor functioning in which participants used their index fingers to push down on a lever rapidly, keeping their palms flat on the board and their fingers extended without moving their hand or arm. The lever is attached to a counting device. The objective was for the participant to tap as quickly as possible within a 10-second period. This process was repeated for both the dominant and non-dominant hands. Z-scores were based on the number of "taps" according to the counting device. The average of these five trials was used to compute the z-score for both the dominant and non-dominant hand. If these five consecutive trials did not occur within the allotted 10 trials, the average of the participant's best five trials was used. A negative z-score indicated that the participant's performance is worse than average, whereas a positive z-score indicated above average performance on the task (Lezak et al., 2004). Based on a sample of 384 people, including controls as well as neurologically stable individuals, test-retest reliability for Finger Tapping over an 11-month period was .77 for the dominant hand and .78 for the non-dominant hand, indicating good test-retest reliability over time (Dikmen et al., 1999).

Premorbid Functioning. *Advanced Clinical Solutions: Test of Premorbid Functioning* (TOPF; Pearson Assessment, 2009a). The TOPF assesses premorbid cognitive functioning, as single word reading ability has a high correlation with IQ. Participants were required to read aloud words printed on the stimulus card. Items were scored as 0 or 1 based on whether or not participants correctly pronounced each word. The TOPF provided a raw score based on the number of correctly pronounced words, and a standard score based on the raw score, which depended on each participant's age. The TOPF has an overall average internal consistency of .98. Based on 293 people, test-retest reliability statistics were calculated over a 21-day period. Test-retest stability statistics were separated by age group; the uncorrected correlation ranged from .90 (16-29 year olds) to .94 (55-69 year olds). However, corrected for variability in the sample, test-retest stability correlations ranged from .89 (16-29 year olds) to .95 (70-90 year olds), indicating good stability over a short period of time (Pearson Assessment, 2009b).

Working Memory. *Wechsler Adult Intelligence Scale – Fourth Edition: Digit Span* (WAIS-IV: Digit Span; Wechsler, 2008a). Digit Span is a subtest within the WAIS-IV that measures working memory in three distinct sections: digit span forward, backward, and sequencing. Specifically, digit span measures sequencing abilities and short term memory. Each section required different cognitive demands, so in order to shift between tasks, cognitive flexibility and mental alertness to the specific instructions for the task at hand was required. Raw scores (number correctly recalled) and scaled scores (based on age of participant) are provided for the total and each section. Digit Span has an overall average internal consistency of

.93. Based on 298 people, test-retest reliability statistics were calculated over a 22-day period (range 8 to 82). The overall test-retest reliability was .82; however, corrected for variability in the sample, the correlation increased to .83 (Wechsler, 2008b).

Wechsler Memory Scale – Fourth Edition: Symbol Span (WMS-IV: Symbol Span; Wechsler, 2009a). Symbol Span is a subtest within the WMS-IV designed to measure visual working memory using novel abstract symbols. Participants were presented with a number of symbols for a five-second period and were required to recall the same designs as well as their order on subsequent pages. As the participant progressed through the task, the number of symbols for each trial increased. Trials were scored as 0 if all the correct symbols were not recalled, 1 if all the correct symbols were recalled, but not in the correct order, or 2 if all the correct symbols were recalled in the correct order. The raw score was the sum of these points (0-53 points). Scaled scores were based on raw scores and depended on the age of the participant (range 1-19; Wechsler, 2009b). Symbol Span has an overall average internal consistency of .84. Based on 244 people (173 completed the adult battery and 71 completed the older adult battery), test-retest reliability statistics were calculated over a 23-day period (range 14 to 84). The overall uncorrected and corrected test-retest reliabilities were both .72 (Wechsler, 2009c).

Visuospatial Abilities. *Motor-Free Visual Perception Test – Third Edition* (MVPT-3; Colarusso & Hammill, 2003a). The MVPT-3 measured visual perceptual abilities using black and white line drawings in five specific skill areas: spatial relationships, visual discrimination, figure-ground, visual closure, and visual memory. The test is divided into nine sections of similar items (65 total questions), all utilizing multiple choice format and specific instructions. After each set of instructions, participants were able to respond to the multiple choice options by either pointing or verbalizing their responses. Reliability statistics were broken down by age group because ages 4-10 were based on items 1-40, and ages 11 and older were based on items 14-65. The median internal consistency for ages 4-10 was .80 (range .69 to .87); the median internal consistency for ages 14-65 was .89 (range .86 to .90). Based on 103 people, test-retest reliability statistics were calculated over an average 34-day period. The 28 children, ages 4-10 had an overall uncorrected test-retest reliability of .82, while the corrected correlation was .87. For the 75 adults, the uncorrected test-retest reliability coefficient was .72, with a corrected correlation of .92 (Colarusso & Hammill, 2003b).

Rey-Osterreith Complex Figure: Copy Trial (ROCF Copy; Meyers & Meyers, 1995). The ROCF measures visuoconstructive abilities. Participants are required to copy an abstract figure from the stimulus card onto a blank sheet of paper. The Copy Trial is a measure of visuospatial constructional skills. Lower raw scores (fewer quality points) indicate a participant's visual-perceptual skills and visuomotor skills are less integrated. Scoring is based on the quality of 18 components of the copied figure. Scores for each component range from 0 (no credit) to 2 (full credit). Three scores are available for the copy trial: the raw score (number of quality points accumulated; max 36), percentile rank based on these quality points, and percentile rank based on time to complete the figure. Across three raters and 15 protocols, the correlation for inter-rater reliability ranged from .93 to .99, with a median coefficient of .94, indicating excellent inter-rater reliability. Based on 12 subjects, test-retest reliability was calculated across an average period of 184 days. However, traditional correlations could not be calculated due to a ceiling effect for the copy trial (Meyers & Meyers, 1995).

CHAPTER III

PROCEDURE

Data Collection

This project was approved by the Institutional Review Board at Central Michigan University. Participants provided written consent and completed two separate phases of the experiment: the virtual reality simulation and the neuropsychological testing. The virtual reality portion provided information regarding participants' motor skills and learning. Data collection for the virtual reality portion took place on two separate occasions with a one-week interval between sessions. The neuropsychological testing portion provided information regarding verbal memory, visual memory, processing speed, executive functioning, motor abilities, premorbid functioning, working memory, and visuospatial abilities, and required approximately 2-2.5 hours to complete. The information was stored in a locked office on campus to ensure confidentiality of participants. All participants completed both portions of the experiment; however, it was made clear that participation was voluntary and participants were able to withdraw at any time. In addition, following completion of each phase, participants were financially compensated for their time.

CHAPTER IV

RESULTS

Sample Characteristics

Demographic information is presented in Table 1. The mean age of participants was 33 (*SD* = 9.40), with an average level of education of 14.31 years (*SD* = 2.80). The two groups did not differ with regard to age; however, the control group was significantly more educated than the patient group, $t(27) = 5.53$, $p < .001$. This difference is indicative of a large effect size (Cohen's $d = 1.56$). Of the 14 patients, one person reported experiencing a loss of consciousness for 27 minutes total (this patient lost consciousness on three separate occasions: 2 minutes, 5 minutes, 20 minutes). Nine patients reported being in a coma, with the average length of time being 29.48 days (*SD* = 26.42, range .33-90 days). One patient was unsure of loss of consciousness, and the other three denied experiencing loss of consciousness or coma. The average time since injury was 10 years (*SD* = 8.01, range .50-22.33 years).

Table 1. *Demographic Information*

Statistics	Total Sample	*SD*	Patients	*SD*	Controls	*SD*
N	29	--	14	--	15	--
Females (%)	15 (52%)	--	7 (50%)	--	8 (53%)	--
M Age	32.97	9.40	32.50	9.44	33.40	9.67
Age Range	18-47		18-44		18-47	
M Education	14.31	2.83	12.21	1.48	16.27***	2.34
Education Range	9-18		9-15		12-18	

Note. ***$p < .01$ *M* = Mean. *SD* = standard deviation

Correlations with time since injury were also examined in order to determine if the length of time post-injury affected results. Statistical analyses showed that time since injury was not significantly related to any of the eight composite scores, nor was it related to the five motor variables from the virtual reality task.

Group Differences on the Virtual Reality Task

Overall Performance

In order to compare performance on the virtual reality task across groups, mean differences were examined using independent samples *t*-tests (see Table 2 for descriptive statistics and effect sizes for each comparison). Each participant's level of overall performance was determined by calculating the average of the ten trials from the virtual reality simulation. Separate calculations were performed for each participant for both days of testing. One participant had only nine trials on Day 2; therefore the average was taken from these nine scores. The control group scored significantly higher than the patient group on both Day 1 and Day 2, $t(27) = 4.92$, $p < .001$; $t(27) = 5.20$, $p < .001$, respectively, suggesting that the control group was capable of performing at a higher level than patients.

Table 2. *Summary of Motor Abilities During the Virtual Reality Task by Group*

	Patients		Controls		
Motor Variable	**Mean**	***SD***	**Mean**	***SD***	**Cohen's *d***
Day 1 Performance	20.06	9.01	33.50***	5.35	1.81
Day 2 Performance	23.38	7.88	35.71***	4.55	1.92
Retention	-2.74	5.39	-2.38	4.25	0.07
Day 1 Rate of Learning	0.68	0.65	0.70	0.86	0.21
Day 2 Rate of Learning	0.45	0.84	0.23	0.45	0.33

Note. *N* = 14 for patient group and 15 for control group. *SD* = standard deviation. ***$p < .001$.

Rate of Learning

Rate of learning was determined by the learning slopes, which were determined by calculating the best-fit regression line using each of the ten performance trials from the virtual reality simulation for each participant. Every participant had two slopes, one for each day. There were no significant mean differences between groups for learning slopes on either Day 1 or Day 2, $t(27) = .079$, $p = .937$; $t(27) = -.875$, $p = .389$, respectively, suggesting that both groups learned at a similar rate.

Figures 1 and 2 visually display both groups' results from the virtual reality portion of the study. Results from paired *t*-tests comparing performance on the first and last trials on each day showed that the control group demonstrated significant improvement across trials on Day 1 and Day 2, $t(14) = 4.26$, $p = .001$; $t(14) = 3.08$, $p = .008$, respectively. However, the patient group significantly improved from the first to the last trial on Day 1 only, $t(13) = 2.83$, $p = .014$.

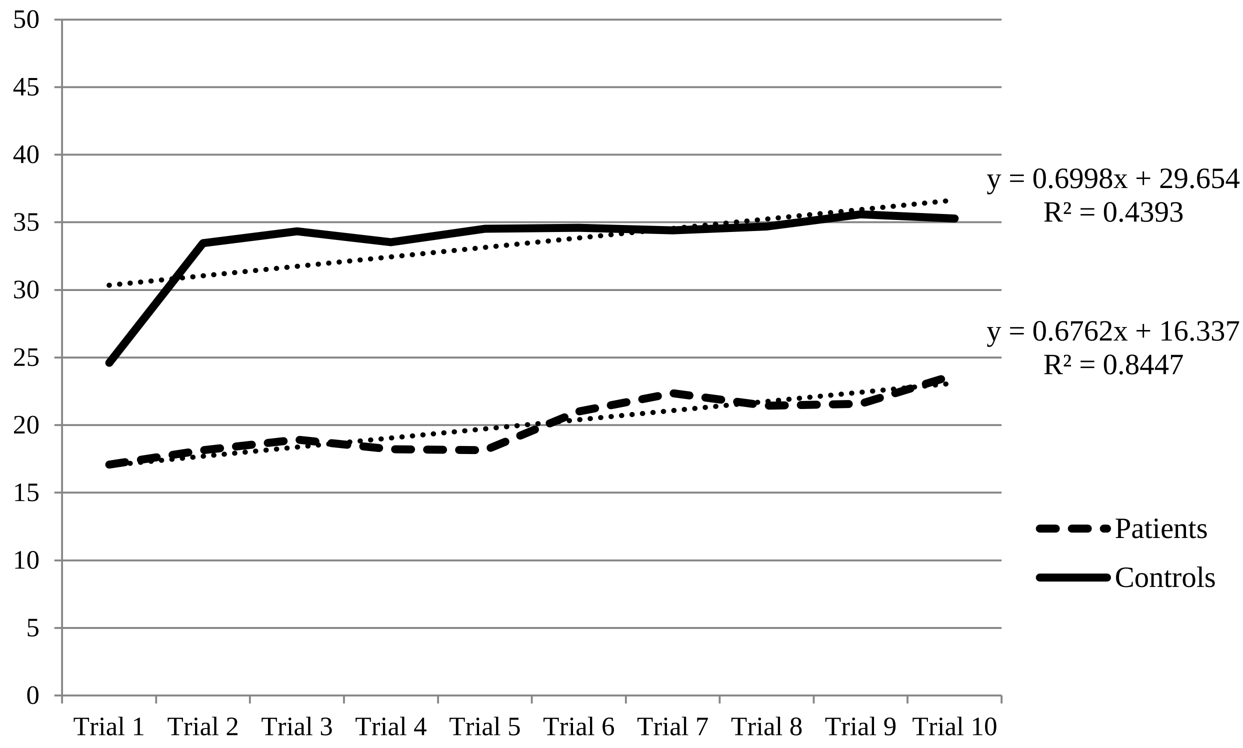

Figure 1. *Day 1 Performance by Group*

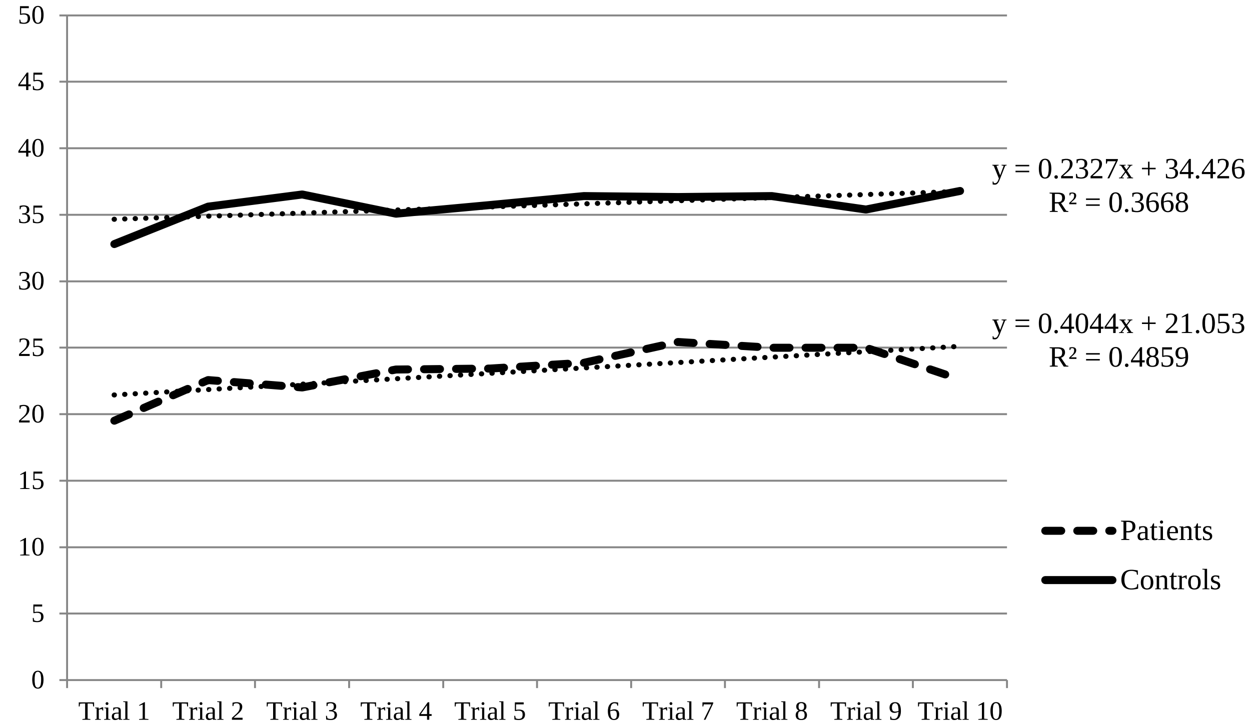

Figure 2. *Day 2 Performance by Group*

Additionally, paired *t*-tests were conducted to examine consecutive trial-by-trial performance differences (e.g. Trial 1 to Trial 2, Trial 2 to Trial 3, Trial 3 to Trial 4, etc.). Results showed that the control group significantly improved their performance from Trial 1 to Trial 2 on Day 1, $t(14) = -6.09$, $p < .001$, and on Day 2, $t(14) = -3.47$, $p = .004$. In contrast, the patient group's increase in performance approached significance from Trial 1 to Trial 2 on Day 2 only, $t(13) = -2.07$, $p = .059$. There were no other significant trial-by-trial improvements made for either group.

Retention was also an area of interest. In order to calculate a retention score, the first trial of Day 2 was subtracted from average of the last three trials of Day 1. The control group did not demonstrate superior retention compared to the patient group, $t(27) = .201$, $p = .842$. Furthermore, the quality of movement was also affected in the patient group. Overall, patients displayed significantly more variability in virtual reality scores than healthy controls on Day 1 ($F = 3.11$, $p = .042$); this difference approached significance on Day 2 ($F = 2.92$, $p = .054$)

Group Differences on Neuropsychological Test Measures

Performance

Descriptive statistics for each neuropsychological test measure and significant group differences are shown in Table 3. The control group consistently performed better than the patient group, with each measure in all eight cognitive domains demonstrating significant differences between groups. In addition to individual test scores, composite scores were also created for each of the eight cognitive domains. All scores were converted into standard scores (z-scores) in order to create the composite score. See Table 3 for a list of measures included in each composite. Cohen's *d* statistics were calculated as a measure of effect size regarding the magnitude of the differences in scores between groups. Each difference between individual measures as well as composite scores was indicative of a large effect size. For participants who were missing data, the composite score consisted of the average of the scores that were available. Two participants were missing scores for the Grooved Pegboard Test and another two participants were missing scores for Finger Tapping.

Table 3. *Individual Test Scores by Group*

Test	Patients Mean	Patients *SD*	Controls Mean	Controls *SD*	Cohen's *d*
Verbal Memory	**-1.63**	**1.26**	**-0.08*** **	**0.93**	**1.40**
CVLT Total 1-5	37.86	11.86	52.93***	7.97	1.49
CVLT Short Delay	-1.71	1.28	-0.13***	1.03	1.36
CVLT Long Delay	-1.96	1.67	-0.40**	1.30	1.04
Processing Speed	**-1.29**	**1.16**	**0.64*** **	**0.63**	**2.07**
SDMT Written	-1.77	1.54	0.86***	1.45	1.76
SDMT Oral	-2.39	1.43	0.38***	1.34	2.00
Trails 1	7.00	3.37	12.73***	1.10	2.29
Trails 2	7.36	4.41	12.00***	2.00	1.36
Trails 3	7.14	4.19	11.93***	2.52	1.39
Color Naming	6.86	4.15	11.53***	2.07	1.42
Word Reading	7.14	4.17	11.60***	1.99	1.37
Executive Functioning	**-1.26**	**0.93**	**0.34*** **	**0.56**	**2.08**
Trails 4	6.07	3.36	11.53***	1.69	2.05
Inhibition	6.86	4.54	12.20***	1.82	1.54
COWAT (F, A, S)	-1.43	0.91	-0.15***	0.86	1.45
COWAT (animals)	-1.27	1.15	0.27***	0.79	1.56
Motor Abilities	**-1.95**	**1.79**	**0.64*** **	**0.43**	**1.99**
Trails 5	7.00	3.60	11.33***	1.88	1.51
Finger Tapping	-1.01	2.21	1.33***	0.89	1.39
Grooved Pegs	-3.91	3.79	0.13***	0.80	1.47
Premorbid Functioning	**-1.05**	**0.86**	**0.13*** **	**0.59**	**1.60**
TOPF	84.29	12.91	102.00***	8.82	1.60
Visuospatial Abilities	**-0.68**	**1.00**	**0.50** **	**0.94**	**1.22**
MVPT	79.71	20.63	115.00***	17.49	1.85
ROCF	26.36	9.28	32.63*	4.30	0.87
Visual Memory	**-1.01**	**1.09**	**0.49*** **	**0.84**	**1.54**
VR-I	6.07	3.83	10.67***	2.80	1.37
VR-II	7.86	2.91	12.27***	2.74	1.56
Working Memory	**-0.85**	**1.06**	**0.58*** **	**0.46**	**1.75**
Digit Span	7.57	3.52	11.73***	2.46	1.37
Symbol Span	7.36	3.10	11.73***	1.71	1.75

Note. *N* = 14 for patient group and 15 for control group. *SD* = standard deviation. CVLT Short and Long Delay, SDMT Written and Oral, COWAT letters and animals, Finger Tapping, and Grooved Pegs values represent z-scores. Trails 1-5, Color Naming, Word Reading, Inhibition, VR I, VR II, Digit Span, and Symbol Span values represent scaled scores. TOPF and MVPT values represent standard scores. CVLT Total 1-5 values represent T-scores. ROCF value represents a raw score. Composite scores are in bold.

[a] * $p < .05$. ** $p < .01$. *** $p \leq .001$.

Correlations

Because education was significantly different between groups, it was controlled for in subsequent correlations. Consequently, given the small sample size, statistical significance may be less interesting than moderate to strong correlations, even if these relationships did not reach statistical significance. See Table 4 for a summary of the correlations among neuropsychological test scores and dependent motor variables for the patient group, and Table 5 for the significant correlations for the control group.

For the patient group, Color Naming from the D-KEFS Color-Word Interference Task and animal naming from the COWAT were significantly positively correlated with overall performance on both Day 1 and Day 2. Additionally, the following individual measures had medium effect sizes (correlations above .36) with overall performance on both Day 1 and Day 2: Letter Sequencing from D-KEFS Trails, Word Reading and Inhibition from the D-KEFS Color-Word Interference Task, , VR-I; these were all positive relationships. Visual Scanning from D-KEFS Trails, TOPF, MVPT, and the ROCF were moderately positively correlated with performance on Day 1 only. Finger Tapping had a positive moderate correlation with overall performance on Day 2 only.

Although none of the composite scores were significantly correlated with performance on either day, processing speed, executive functioning, and visuospatial abilities were the three cognitive domains that yielded positive moderate correlations for the patient group on both days. Premorbid functioning and visual memory demonstrated moderate positive correlations on Day 1 only.

In contrast, the control group demonstrated fewer moderate and significant correlations with overall performance. Word Reading was the only significant correlation with performance on Day 1, although Visual Scanning, Color Naming, Finger Tapping, and the Motor Abilities composite score were moderately correlated; these were all negative relationships. On Day 2, both the Executive Functioning composite score and the Motor Abilities composite score were significantly negatively correlated with performance. Inhibition was the only individual measure demonstrating a significant correlation, which was also negatively related; SDMT oral, Word Reading, Number-Letter Switching from D-KEFS Trails, the letter portion of the COWAT, Grooved Pegs, and the Working Memory composite score demonstrated moderate negative correlations.

Correlations between rate of learning and neuropsychological measures produced a different pattern of results. For the patient group, rate of learning on Day 1 was significantly negatively correlated with the total score on the five immediate recall trials of the CVLT, the written version of the SDMT, and Motor Speed from D-KEFS trails; none of these measures however, yielded even moderate correlations on Day 2. Conversely, moderate negative correlations with rate of learning on Day 1 existed with the Verbal Memory composite score, CVLT Long Delay, the oral version of the SDMT, the Visuospatial Abilities composite score, MVPT, and Symbol Span. The only moderate correlation that remained on Day 2 was the CVLT Long Delay. Day 2 yielded moderate correlations between rate of learning and Color Naming, the Motor Abilities composite score, and Grooved Pegs.

Table 4. *Correlations Among Neuropsychological Test Scores and Dependent Motor Variables With the Effects of Education Partialled Out for the Patient Group*

Test	Day 1 Performance	Day 2 Performance	Day 1 ROL	Day 2 ROL	Retention
Verbal Memory	**.330**	**.088**	**-.522**	**-.233**	**.192**
CVLT Total 1-5	.283	.006	-.680*	-.125	.154
CVLT Short Delay	.341	.147	-.312	-.002	-.024
CVLT Long Delay	.294	.076	-.502	-.424	.340
Processing Speed	**.412**	**.377**	**-.320**	**-.089**	**.164**
SDMT Written	.035	-.074	-.698*	.119	.234
SDMT Oral	.180	.034	-.539	.084	.229
Trails 1	.366	.331	-.233	.042	-.315
Trails 2	.297	.280	-.321	-.153	.051
Trails 3	.377	.368	-.230	.026	.187
Color Naming	.638*	.692*	.041	-.406	.284
Word Reading	.476	.544	.155	-.198	.113
Executive Functioning	**.575**	**.569**	**-.096**	**-.208**	**.180**
Trails 4	.050	.107	-.353	.023	.409
Inhibition	.494	.538	.008	-.281	.293
COWAT (F, A, S)	.288	.191	-.354	-.047	.173
COWAT (animals)	.841**	.791**	.265	-.245	-.320
Motor Abilities	**.230**	**.231**	**-.085**	**.380**	**-.170**
Trails 5	-.050	-.123	-.640*	.227	.027
Finger Tapping	.351	.501	.299	.308	-.333
Grooved Pegs	.209	.167	-.096	.381	-.123
Premorbid Functioning	**.382**	**.096**	**-.136**	**-.273**	**-.115**
TOPF	.382	.096	-.136	-.273	-.115
Visuospatial Abilities	**.578**	**.372**	**-.418**	**-.233**	**.153**
MVPT	.555	.329	-.431	-.271	.089
ROCF	.379	.321	-.191	-.025	.258
Visual Memory	**.514**	**.320**	**-.014**	**.110**	**-.300**
VR-I	.622	.415	.057	-.033	-.246
VR-II	.299	.145	-.116	.306	-.347
Working Memory	**.263**	**.121**	**-.310**	**-.195**	**.249**
Digit Span	.146	.103	-.190	-.123	.310
Symbol Span	.358	.130	-.405	-.252	.169

Note. $N = 14$. ROL = rate of learning. $^{*}p \leq .05$, $^{**}p < .01$.

In the control group, the Verbal Memory composite score was related to rate of learning on both days, with a significant positive correlation on Day 1, and a moderate negative correlation on Day 2. Similarly, the total score on the five immediate recall trials of the CVLT was also significantly correlated on both days, with a positive association on Day 1, and a negative association on Day 2. Although Finger Tapping was related to rate of learning on both days, it was positively significantly correlated on Day 2, with a moderate negative correlation on Day 1, and the oral version of the SDMT was moderately correlated on both days (positive on Day 1 and negative on Day 2). The following neuropsychological predictors were also moderately positively correlated on Day 1: CVLT Short Delay, CVLT Long Delay, Processing Speed composite score, the written version of the SDMT, Number Sequencing, Color Naming, and Word Reading. The Visual Memory composite score and VR-II had moderate negative correlations on Day 1 as well. Finally, the Motor Abilities composite score and Finger Tapping had significant positive associations with rate of learning on Day 2 only.

With regards to retention, Number-Letter Sequencing from the D-KEFS Trails was the only neuropsychological measure that was moderately correlated with retention in the patient group; this relationship was positively associated. Conversely, this was not the case in the control group. The Executive Functioning composite score, Inhibition, and Grooved Pegs were all significantly negatively correlated with retention in the control group. Additionally, the Processing Speed composite score, Word Reading, Number-Letter Sequencing, the animal portion of the COWAT, the Working Memory composite score, and Digit Span were all moderately negatively correlated with retention for control participants. The MVPT had a moderate positive association with retention in the control group.

Table 5. *Correlations Among Neuropsychological Test Scores and Dependent Motor Variables With the Effects of Education Partialled Out for the Control Group*

Test	Day 1 Performance	Day 2 Performance	Day 1 ROL	Day 2 ROL	Retention
Verbal Memory	**-.161**	**-.210**	**.606***	**-.470**	**-.276**
CVLT Total 1-5	.036	.123	.726**	-.619*	-.174
CVLT Short Delay	-.304	-.238	.534	-.285	-.196
CVLT Long Delay	-.108	-.323	.434	-.414	-.328
Processing Speed	**-.256**	**-.297**	**.489**	**-.217**	**-.371**
SDMT Written	-.019	-.180	.363	-.335	-.239
SDMT Oral	-.063	-.222	.425	-.415	-.318
Trails 1	-.422	-.374	.175	.303	-.258
Trails 2	-.150	-.160	.420	-.261	-.169
Trails 3	-.037	-.055	.283	-.064	-.269
Color Naming	-.450	-.237	.430	.153	-.273
Word Reading	-.674*	-.471	.422	.139	-.394
Executive Functioning	**-.328**	**-.581***	**.193**	**-.106**	**-.581***
Trails 4	-.243	-.472	.230	-.160	-.383
Inhibition	-.329	-.689**	.031	.250	-.780**
COWAT (F, A, S)	-.336	-.445	-.026	-.147	-.301
COWAT (animals)	-.115	-.251	.346	-.190	-.398
Motor Abilities	**-.477**	**-.620***	**-.293**	**.660***	**-.341**
Trails 5	-.210	.003	.126	.255	.063
Finger Tapping	-.383	-.406	-.469	.617*	.016
Grooved Pegs	-.131	-.525	-.001	.099	-.648*
Premorbid Functioning	**-.063**	**-.147**	**-.055**	**.237**	**-.009**
TOPF	-.063	-.147	-.055	.237	-.009
Visuospatial Abilities	**.139**	**.072**	**-.249**	**.032**	**.326**
MVPT	.166	.105	-.189	-.034	.423
ROCF	.075	.017	-.259	.101	.139
Visual Memory	**.136**	**-.237**	**-.367**	**.133**	**-.270**
VR-I	.030	-.196	-.257	.169	-.153
VR-II	.243	-.252	-.446	.074	-.372
Working Memory	**-.275**	**-.472**	**.202**	**-.103**	**-.456**
Digit Span	-.372	-.283	.334	-.021	-.375
Symbol Span	.115	-.259	-.162	-.110	-.120

Note. $N = 15$. ROL = rate of learning. *$p \leq .05$, **$p < .01$.

Composite Score Correlations

The composite scores were correlated with each other in order to determine if multicollinearity may be an issue in further analyses. These correlations are shown in Table 6 for the patient group and Table 7 for the control group. The majority of the cognitive domains were significantly positively related to each other in the patient group. The control group demonstrated five significant correlations among composite scores, suggesting that these eight cognitive domains are less related to each other in control participants than in patients. These results suggest that because the independent variables are highly related to one another, the standard errors in further analyses may be misleadingly inflated, providing inaccurate results. Therefore, because of this multicollinearity, hierarchical regression analyses with these eight independent variables were not feasible.

Table 6. *Correlations Among Cognitive Composite Domains for the Patient Group*

Composite Domain	1	2	3	4	5	6	7	8
1. Verbal Memory	1	--	--	--	--	--	--	--
2. Processing Speed	.773**	1	--	--	--	--	--	--
3. Executive Functioning	.699**	.957**	1	--	--	--	--	--
4. Motor Abilities	.690**	.763**	.726**	1	--	--	--	--
5. Premorbid Functioning	.633*	.522	.539*	.485	1	--	--	--
6. Working Memory	.870**	.878**	.836**	.691**	.701**	1	--	--
7. Visuospatial Abilities	.810**	.854**	.826**	.709**	.606*	.794**	1	--
8. Visual Memory	.648*	.673**	.656*	.765**	.659**	.695**	.828**	1

Note. $N = 14$. $^{*}p < .05$. $^{**}p \leq .01$.

Table 7. *Correlations Among Cognitive Composite Domains for the Control Group*

Composite Domain	1	2	3	4	5	6	7	8
1. Verbal Memory	1	--	--	--	--	--	--	--
2. Processing Speed	.706**	1	--	--	--	--	--	--
3. Executive Functioning	.592*	.624*	1	--	--	--	--	--
4. Motor Abilities	.004	.430	.373	1	--	--	--	--
5. Premorbid Functioning	.191	.194	.275	.226	1	--	--	--
6. Working Memory	.543*	.201	.660**	.070	.377	1	--	--
7. Visuospatial Abilities	-.190	-.232	.042	.310	.410	.097	1	--
8. Visual Memory	.257	.233	.342	.280	.173	.167	.249	1

Note. $N = 15$. $^{*}p < .05$. $^{**}p < .01$.

Regression Analysis

Because all of the eight cognitive domains were significantly related to one another in the patient group, a single Global Ability Index was created, using the average of the eight z-scores from each domain. Using this composite variable, hierarchical regression analyses were performed to evaluate whether this Global Ability Index explained a significant amount of unique variance in overall performance and overall rate of learning for the total sample. Demographic variables including education, gender, and age were entered in the first block, and the Global Ability Index was entered in the second block.

Results of the hierarchical regression analysis for variables predicting overall performance are shown in Table 8. In the total sample, the demographic variables (education, gender, and age) explained 47% of the variance in overall performance, which was significant, $R^2 = .470$, $F(3,25) = 7.393$, $p = .001$. The Global Ability Index added 9.8% of variance over and above the demographic variables, which was also statistically significant, $\Delta R^2 = .098$, $\Delta F(1,24) = 5.479$, $p = .028$. Together, the demographic variables and the Global Ability Index jointly explained 56.9% of the variance in performance, which was significant, $R^2 = .569$, $F(4,24) = 7.908$, $p < .001$. Examination of the coefficients for the final model revealed that the Global Ability Index had the greatest contribution in predicting overall performance ($\beta = .471$).

Next, the same hierarchical regression analysis was performed to examine the relationship between demographic variables, the Global Ability Index, and participants' rate of learning. Neither the demographic variables nor the Global Ability Index separately explained a significant portion of variance in rate of learning; furthermore, when all variables were entered into the final model, all four variables only explained 13.7% of the variance in rate of learning, which was not significant.

Table 8. *Hierarchical Regression Analysis for Variables Predicting Overall Performance*

Variable	*F*	*df*	R^2	ΔR^2	*B*	*SE B*	β
Step 1							
Demographic Variables	7.393**	3,25	.470	.470**			
Age					-.109	.144	-.112
Gender					.834	2.675	.046
Education					2.180	.475	.673**
Step 2							
Demographic Variables							
Age					-.040	.136	-.041
Gender					.649	2.465	.036
Education					1.066	.646	.329
Global Ability Index	7.908**	4,24	.569	.098*	3.909	1.670	.471*

Note. $N = 29$. *B* = unstandardized regression coefficient, *SE B* = standard error of *B*, β = standardized regression coefficient. $*p < .05$. $**p < .01$.

CHAPTER V

DISCUSSION

The current study investigated the relationship between cognitive ability and performance on a virtual reality task in healthy controls and individuals with a history of TBI. The purpose of this study was to allow the researchers to evaluate the impact of cognitive deficits on motor learning.

Consistent with hypotheses, the control group exhibited a higher level of overall performance than the patient group across both days of virtual reality testing. Results were also consistent with both Cirstea and colleagues' (2003) and Winstein and colleagues' (1999) findings that overall, both groups' performance significantly improved across trials (with the exception of Day 2 for the patient group). Furthermore, these two previously mentioned studies also found that the quality of movement was affected in their patient groups; this result was also found in the current study, as the patients displayed significantly more variability in virtual reality scores than healthy controls on Day 1, with a trend on Day 2.

It was hypothesized that both the patient and control group would exhibit learning across trials, but that the control group would learn at a faster rate. However, the current findings did not support this hypothesis and differ from results of previous literature. Results indicated that both groups learned at a similar rate. Analyses also showed that the rate of learning did not differ within groups either, from Day 1 to Day 2.

While TBI did not affect a person's rate of learning on a relatively basic motor task, these findings may be confounded by task difficulty, as all participants reached their maximum potential within a few trials, leaving minimal opportunity for learning. Thus, there may not have been the opportunity for participants to demonstrate variable learning rates.

This inconsistency with the previous literature may be explained by Catena and colleagues' research (2007, 2009) regarding task difficulty. Briefly, these researchers found that their tasks were not challenging enough to produce differences between groups regarding secondary motor tasks. Likewise, results from the current study suggest that the virtual reality task may not have been challenging enough to produce differences between groups, specifically regarding rate of learning. In fact, the only significant improvements that were made from trial to trial were between trials 1 and 2 on the first and second day for the control group; this improvement approached significance on the second day only for the patient group. This finding further supports the notion that both groups reached their full potential quickly. Therefore, there was not an opportunity for participants in either group to demonstrate learning across trials.

In addition to group differences, the other main purpose of the current study was to examine how cognitive functioning is related to motor learning by analyzing the relationship between eight cognitive domains and performance on the virtual reality measure for the patients and healthy controls. In general, correlations between neuropsychological test measures and motor variables from the virtual reality task yielded differing patterns of results.

Regarding overall performance on individual measures, it was hypothesized that neuropsychological test scores relating to motor performance, visual memory, and visuospatial abilities would be more highly correlated with level of performance in both groups than the other cognitive measures. Results of individual test measures support this hypothesis regarding the latter two domains for the patient group, mainly on Day 1. Although not statistically significant, measures of visual memory and visuospatial abilities were moderately correlated with performance.

With regard to motor functioning, this hypothesis was only partially supported. In the patient group, Finger Tapping, a measure of gross motor movements, was somewhat correlated with performance on Day 1, but moderately correlated with performance on Day 2. Additionally, Motor Abilities as a whole was significantly correlated with performance on Day 2 for the control group. Again, Finger Tapping was to some extent correlated on both days. The virtual reality task required participants to make only broad motor movements, which may have explained why there were no differences in fine motor skills. Additionally, Day 1 may have emphasized cognitive effort to determine the best approach to the task, while Day 2 emphasized dexterity.

Although the motor functioning hypothesis was only partially supported, (as these correlations mainly existed within the patient group), several other unexpected relationships were also found. Measures of processing speed were associated with overall performance on both days in the patient group. Additionally, contrary to hypotheses, executive functioning also showed a relationship with performance on both days for the patient group and Day 2 for the control group.

As patients learned the virtual reality task, correlations between neuropsychological test measures and their virtual reality performance tended to decrease across domains. Fluid reasoning skills, or those important in novel situations, were less relevant and were not significant on Day 2 of the virtual reality task (premorbid functioning, visuospatial abilities, visual memory) potentially because participants were already acclimated to the requirements of the task. Additionally, these results were not due solely to physical limitations because the patient group displayed difficulty with many cognitive functions, as demonstrated by the Global

Ability Index. The hierarchical regression analysis showed that this Global Ability Index explained an additional 9.8% of variance over and above demographic variables.

The hypotheses regarding correlations with rate of learning were generally supported, as verbal memory was associated with learning over time. The total of the immediate trials was a significant predictor of rate of learning on both Day 1 and Day 2. Finger Tapping was the only motor measure that was related to both patient and control participants' rate of learning. Furthermore, it was hypothesized that neuropsychological measures related to memory would be correlated with the retention score from the virtual reality phase. This hypothesis was only partially supported. Within the control group, only working memory was associated with retention average.

Limitations

The current study has several limitations. The patient and control groups had 29 combined participants, limiting the power to detect small effects. Type I error must also be considered; this concept may have also helped to explain the surprising direction of several of the correlations. Both small sample size and an abundance of analyses can contribute to spurious results. Along with small sample size and Type I error, perhaps one of the principal limitations of the current study was the difference in education between groups. Because of this difference, partial correlations were necessary in order to control for the effects of education, and partial correlations lower power.

Additionally, multicollinearity among independent variables made it difficult to examine the predictive relationship between individual cognitive domains and the motor variables from the virtual reality portion of the study because hierarchical regression analyses were not feasible.

Therefore, this study was only able to focus on overall ability level via the Global Ability Index, which consisted of all eight domains.

A further limitation was that the participants in the experimental group had experienced varying degrees of TBI severity. Research has shown that the more severe the brain injury, the larger the effect on learning (Boyd, Quaney, Pohl, & Winstein, 2007; Cirstea et al., 2003). Patient screening did not include a thorough medical background; therefore, the location of brain damage was unknown. The fact that the damaged area was unknown introduced more variability within the patient group, making it difficult to compare across individuals because damage to varying areas may present differently and affect the outcome of the neuropsychological test results.

Finally, the age dispersion of participants was rather large (range 18-47). Kleim and Jones (2008) indicate that learning is affected by age; as a person ages, the neural plasticity decreases. Along these lines, there may also have been some effect of age at injury, given that the brain, especially the frontal lobe, continues to development into early adulthood. Although neuropsychological test scores were calculated using age-based norms, age may have indirectly affected results if examined from a neural plasticity viewpoint.

Conclusions

As the majority of the literature has focused primarily on individuals with stroke, the results from the current study are important because they extend the current literature by examining the same concepts in individuals with TBI. The current results may provide a starting point for other virtual reality studies and rehabilitation programs, specifically regarding which cognitive domains should be the focus of improvement. Future studies can use the current findings regarding differences in correlations as a way to generate future hypotheses and guide research. However, these results should be taken with care, as the study was conducted with a small sample size. Future research should consider using a larger sample size, experimental participants with similar injury sites, and participants of a more restricted age and education range to control for confounding effects.

APPENDIX

DETAILED INTRODUCTION

Current statistics indicate that over 1.7 million Americans experience a traumatic brain injury (TBI) every year (Faul, Xu, Wald, & Coronado, 2010). Of these incidents, it is estimated that over 52,000 people die, over 275,000 people are hospitalized, and 125,000 people are disabled one year post-injury (Dikmen et al., 2009; Faul et al., 2010). In addition, Flanagan, Cantor, and Teresa (2008) indicate that prevalence rates are expected to rise due to the aging population and the increased risk and poorer outcome associated with TBI for this group. "This will greatly increase the overall prevalence of TBI and add to the societal burden presented by more individuals requiring both medical and custodial care" (Flanagan et al., 2008, p. 877). Therefore, rehabilitation programs have become extremely important for these particular populations.

Although virtual reality is not new to the field of medicine, it is a relatively new concept related to therapy and rehabilitation (Cherniack, 2011; Holden, 2005; Mumford & Wilson, 2009). One of the key concepts of rehabilitation is that of motor learning, which can be defined as an internal process that results in a relatively permanent change in an individual's capability to perform a motor task (Kerr, 1982; Magill, 2004; Schmidt & Wrisberg, 2004). Some of the most common components of this process include practice, repetition, and feedback (Holden, 2005; Sullivan, 2007; Wulf, Shea, & Lewthwaite, 2010). Although traditional rehabilitation programs incorporate these components, it has been suggested that with the continuing advancements in technology, virtual reality may provide supplementary benefits including easier manipulation of environments and a more intense learning experience (Levin, 2011).

Additional advantages of rehabilitation utilizing virtual reality have been examined, including its game-like presentation and motivational features. A common barrier to treatment is the patient's lack of motivation, which is crucial to successful motor rehabilitation (Holden, 2005). Studies have shown an increased level of motivation, enthusiasm, and enjoyment in participants in rehabilitation programs that utilize virtual reality (Sveistrup, 2004; Thornton et al., 2005). For example, Thornton and colleagues (2005) compared the perceptions of individuals assigned to a more traditional, activity-based exercise group to individuals assigned to a virtual reality-based exercise group and found that the virtual reality participants were more engaged and interested during their sessions. Furthermore, comments from caregivers indicated that participants looked forward to their sessions.

With virtual reality simulations, participants are provided with a safe environment that poses minimal risk. This environment is particularly important for rehabilitation skills such as driving (Flanagan et al., 2008; Schultheis, Himelstein, & Rizzo, 2002). Other rehabilitation programs have been developed in order to enhance skills for independent living including cooking and navigation (Flanagan et al. 2008; Schultheis et al., 2002). Rand, Katz, and Weiss (2009) implemented a virtual supermarket called the VMall (Rand, Katz, Shahar, Kizony, & Weiss, 2005) for patients with stroke who experienced weakness in the upper extremities. Participants selected aisles as well as reached for grocery products with their weak extremity with the ultimate goal of improving functioning. Participants showed improvement on all outcome measures, including two functional assessments, a questionnaire, and a short interview with the patient. Post-intervention, an additional questionnaire demonstrated that the gains made in therapy transferred to the real world. Participants reported using two hands and using their arms more spontaneously for daily tasks.

Psychological assessment and rehabilitation for individuals with TBI and neurodegenerative disorders, as well as individuals with attention difficulties including attention deficit hyperactivity disorder (ADHD), have also utilized virtual environments (Cherniak, 2011; Rizzo et al., 2000). For example, Cushman, Stein, and Duffy (2008) created a virtual environment in order to detect early navigational impairment common in mild cognitive impairment and early Alzheimer's disease. Participants also included two control groups of young normal controls (M = 23.18 years) and older normal controls (M = 73.40 years); all groups were randomly assigned to do either the real-world testing or virtual testing first. The virtual environment modeled the real-world environment of the hospital in which the study took place. The researchers found a strong correlation between the real-world test scores and virtual test scores across groups (r = .73). However, virtual environment scores were uniformly lower than real-world scores. There were significant group differences in performance such that young normal controls performed the best, followed by older normal controls, the mild cognitive impairment group, and finally, the early Alzheimer's disease group. These results suggest that navigational testing in a virtual environment is comparable with real-world testing.

Furthermore, in an effort to increase ecological validity, virtual reality has been used in a variety of settings including rehabilitation, and neuropsychological assessment purposes as well. Traditional neuropsychological measures do not capture the full complexity of the demands of day-to-day functioning, therefore, the predictive ability of traditional measures has been questioned (Rizzo, Schultheis, Kerns, & Mateer, 2004). Typical measures tend to assess one isolated aspect of functioning; however, the real world requires integration of many skills (Matheis et al., 2007). Virtual reality-based assessment allowS for inclusion of complex challenges that are naturally found in the real-world, not only increasing relevance of the task itself, but improving predictive validity (Rizzo & Kim, 2005). Additionally, having flexibility and full control over the presentation of stimuli to provide functionally relevant scenarios unique to each participant increases ecological validity as well (Rizzo & Kim, 2005; Schultheis et al., 2002).

Zhang and colleagues (2003) found that by utilizing virtual reality, tasks can be frequently repeated and the experimenter is able to easily manipulate the level of assistance the patient receives. The researchers used a meal planning scenario in a virtual kitchen environment for rehabilitation purposes in 54 individuals with TBI in order to examine reliability and validity of the simulation. Results demonstrated that the virtual kitchen showed both good reliability and concurrent validity in assessing cognitive abilities in individuals with TBI. Additionally, Matheis and colleagues (2007) compared a group of patients with moderate to severe TBI to healthy controls in a virtual reality office environment. This specific study was designed to explore how a list-learning memory task in a virtual environment compared to standard neuropsychological testing. Researchers found that this memory task was able to differentiate patients from controls; however, recall indices from the virtual environment and from the California Verbal Learning Test (CVLT) demonstrated a significant correlation only for recall after 30 minutes. While this finding provides some evidence for convergent validity between the two measures, the researchers attributed these differences to the fact that the virtual reality task presented stimuli verbally and visually, which may have provided an environmental advantage. In addition, the researchers state that this advantage represents the environment in which professionals attempt to generalize findings (Matheis et al., 2007). Schultheis and colleagues (2002) provide evidence from a number of studies for the effectiveness of virtual reality in a variety of settings as well as for the assessment of many cognitive functions such as executive functions, attentional processes, visuospatial processes, and memory functions as either a replacement for, or as a supplement to, traditional neuropsychological assessment methods.

In 2009, Mumford and Wilson conducted an extensive review of the literature specifically related to virtual reality and acquired brain injury; they found that the majority of research focused almost exclusively on patients with stroke, and that studies which examined patients with TBI were lacking. Likewise, Rand et al. (2009) noted that interventions for motor deficits that utilize virtual reality have mainly focused on individuals with stroke. While the field is broadening its scope, there is still a lack of research regarding virtual reality and TBI specifically.

In addition to physical difficulties, individuals who experience TBIs can be affected by cognitive deficits such as slowed information processing, attentional problems, memory deficits, and problems with executive functioning (Dikmen et al., 2009; Eslinger, Zappalá, Chakara, & Barrett, 2007). These cognitive processes play an important role in the ability to learn in general (Robinson-Riegler & Robinson-Riegler, 2004). More specifically, information processing includes encoding, consolidation, and retrieval processes. Encoding is the process in which information is acquired and consolidation is the process for creating and maintaining neural pathways necessary to retrieve information from memory (Eslinger et al., 2007). Problems with attention can lead to difficulties for the patient in everyday life because one of the primary purposes of attention is to allocate ample resources for all other cognitive functions (Cohen, Malloy, Jenkins, & Paul, 2006). If the patient is not able to sustain attention, he or she will not be able to comprehend new information, therefore making all other processes difficult. Any number of these processes may be damaged in patients with TBIs, thus affecting their ability to learn novel tasks.

Rehabilitation may focus on a variety of novel tasks; however, one common area of interest involves novel motor movements. The sequence of motor production begins before the initial movement. Many neural structures are involved in transforming an idea into implementation of a motor movement, and these structures are hierarchically organized. Areas of the posterior cortex are important for providing specific movement goals as well as sensory information to the prefrontal cortex, which subsequently transforms these goals into a specific plan (Kolb & Whishaw, 2009). The instructions provided by the prefrontal cortex then travel to the premotor cortex. This area also receives sensory information from a variety of areas of the brain including the parietal and temporal lobes (Carlson, 2007). Information from the temporal lobe contains qualitative characteristics for recognition of what a person perceives, whereas the parietal lobe conveys information regarding spatial configuration (Gazzaniga, 2009). The premotor cortex uses this sensory information to organize the appropriate sequence of movements (Carlson, 2007; Kolb & Whishaw, 2009). Once the sequence is determined, the nerve impulses travel to the primary motor cortex, where the signals for movement are disseminated to the rest of the body through a variety of tracts (Benarroch, Daube, Flemming, & Westmoreland, 2008; Carlson, 2007). More specifically, the nerve impulses containing the appropriate movements are transmitted from the primary motor cortex to the brainstem, the bridge between the cerebrum and the spinal cord. These impulses travel through the spinal cord and are transmitted to components of the peripheral nervous system and voluntary muscles for the execution of motor movement.

The motor system also consists of two control circuits that include the cerebellum and basal ganglia, both of which have connections with the premotor and primary motor cortices as well as the motor tracts in the brainstem (Benarroch et al., 2008). The cerebellum is important in acquiring and maintaining motor skills (Kolb & Whishaw, 2009). The connections between the cerebellum and the thalamus provide the means of communication for controlling the coordination and movement of the limbs and trunk (Filley, 2008). In addition, the cerebellum is also involved in posture and equilibrium as well as timing and error correction of movements (Benarroch et al., 2008).

Similar to the cerebellum, the basal ganglia also have connections with the thalamus that facilitate control of voluntary movements. The basal ganglia consist of a variety of structures that are important for procedural learning, or the planning and execution of new motor skills (Doyon et al., 2009). Together, these structures are involved in a variety of functions including automatic execution and simultaneous suppression of competing movements, and in determining the appropriate amount of force and duration for the given situation (Benarroch et al., 2008). Nerve impulses may take one of two pathways through the basal ganglia: a direct pathway which has an inhibitory effect on movement, or an indirect pathway which has an excitatory effect on movement (Carlson, 2007). Damage to the basal ganglia may also result in disturbances in motor functioning such as the rigidity displayed in Parkinson's disease, caused by the deprivation of dopamine in the motor system (Grahn, Parkinson, & Owen, 2009).

It is also important to understand the concepts of implicit and explicit memory when referring to motor learning. Explicit memory can be described as those memories in which the individual is consciously aware. These memories can be broken down into semantic memory, or memory for factual information, and episodic memory, or events from one's own life. In contrast, implicit memory occurs unconsciously; for example, skills such as riding a bike, using language, or playing sports are all considered implicit memories (Kolb & Whishaw, 2009). Thus, memory for motor movements, or procedural memory would be considered to be in the realm of implicit memory. The basic anatomy of implicit memory consists of the following primary neural structures: the basal ganglia, motor cortex, and cerebellum. A disruption these systems may cause difficulty with implicit memory. In the past, research has assumed that explicit and implicit systems are entirely separate; however an increasing amount of work has been providing evidence to the contrary. The following sections discuss the concept of the dual-task paradigm as it applies to motor learning and cognitive functioning.

In order to successfully apply these concepts to patients with TBI, it is first necessary to understand how cognitive functioning affects motor learning. Much of the literature has focused on research regarding the dual-task paradigm. This type of design requires participants to complete a number of tasks separately and then simultaneously to examine the change in performance when the tasks are combined. A recent meta-analysis found that dual-task paradigms require the use of higher-order cognitive systems that, in turn, influence gait control. Results indicated that when participants engaged in a dual-task paradigm, their performance was slowed, indicating that control of gait requires resources from higher-order systems (Al-Yahya et al., 2011). This effect was prevalent across different populations, including older adults and individuals with neurological disorders, as well as for a variety of cognitive tasks consisting of mental tracking, working memory, and verbal fluency. The researchers also found that these cognitive tasks influenced many aspects of motor functioning including a decrease in cadence, and increases in stride length, stride time, and stride time variability (Al-Yahya et al., 2011).

Research has also been conducted examining neuropsychological test scores as predictors of gait performance using a healthy elderly sample (Holtzer, Verghese, Xue, & Lipton, 2006). The researchers examined test scores from a variety of neuropsychological measures in a sample of 186 cognitively healthy older adults. They performed a factor analysis that resulted in three factors consisting of verbal IQ, executive attention, and memory. The participants performed a pure motor task, as well as a simultaneous verbal interference task. The researchers found that the amount of variance accounted for by each of the factors depended on which task participants were performing. All three factors were significant predictors of gait speed when participants performed only the motor task; however, when the interference task was added, only speed/executive attention and memory significantly predicted gait speed. In addition, they also add that because these three factors do not exclusively predict gait, this suggests that cognitive processes related to gait are multifaceted and thus have both shared and independent neural correlates. Holtzer and colleagues (2006) explained that the interference condition is more like reality, and suggest that speed/executive attention and memory may be especially important regarding walking in the real environment, where multiple stimuli are present.

Some researchers have postulated that the associated decline of both cognitive and motor functioning is evidence for a common pool of resources or shared process of cognitive and motor abilities, with evidence from dual-task performance strengthening their argument (Catena, van Donkelaar, & Chou, 2007, 2009; Sosnoff, Broglio, & Ferrara, 2008). In both of their studies, Catena and colleagues (2007, 2009) compared gait and balance performance using a dual-task paradigm in groups of individuals who have experienced concussions, versus matched controls. In 2007, the researchers found that the concussed group displayed differences in gait with both a simple walking task and with a more complex secondary task. They postulated that the decline in gait performance resulted from a decrease in attentional resources due to mild TBI; more specifically, they indicated that this decline may be related either to an increased demand for resources to process locomotive information, or a decline in the capacity to process information in general (Catena et al., 2007). In both studies, the researchers found that the simpler tasks (reaction time and uninterrupted walking) were not challenging enough to produce an effect and that as task difficulty increased, performance subsequently decreased (Catena et al., 2007, 2009). In addition to task difficulty, other characteristics of the tasks performed in this paradigm may also affect performance. For example, concepts such as familiarity of the task may determine performance, with more familiar or overlearned tasks being easier for participants to complete simultaneously than a novel task that may require more attentional resources to accomplish (McCulloch, 2007).

Sosnoff and colleagues (2008) compared cognitive and motor abilities in 36 collegiate athletes pre- and post-mild TBI. The researchers found that, prior to injury, these abilities were independent of one another; however, post-injury, there was a decrease in both areas as well as a strong correlation between cognitive and motor abilities. Results provided evidence for two possible outcomes: mild TBI reduces the cognitive resources available to individuals, thus decreasing performance in each domain, or that cognitive and motor functions share a common process, which in turn affects performance on each task. However, like the results from Catena and colleagues' studies (2007, 2009), it may also be the case that the dual task was not challenging enough for the individuals prior to sustaining a TBI, thus concealing any possible effect at baseline.

Additional evidence of decreased performance on motor abilities in the TBI population has focused specifically on several aspects of gait (Parker, Osternig, Lee, van Donkelaar, & Chou, 2005; Vallee et al., 2006). Parker and colleagues (2005) examined various aspects of gait performance for a level walking task without obstructions compared to a more complicated dual task involving walking while performing a number of cognitive tasks in a group of ten individuals with concussions compared to a control group. They found that the dual-task condition resulted in significant changes in gait, including shorter stride length, longer stride time, and center of mass measurements for both groups; however, individuals with concussion displayed significantly greater center of mass sway that the researchers suggest may be because of a deficit in their ability to accomplish both tasks due to brain injury. Similarly, Vallee and colleagues (2006) examined motor abilities using a more complex motor task that involved narrow and wide obstructions in addition to cognitive tasks that included portions of the stroop test. Results indicated that performance was similar in both groups for the simpler tasks including the unobstructed walking task, and naming colors from the stroop test. However, for more complex tasks, the researchers found group differences for both types of obstacles, and performance was most affected in the dual-task condition combining the wide obstacle with the simultaneous inhibition portion of the stroop test (Vallee et al., 2006).

How does performance in these dual-task paradigms relate to the previously discussed neuroanatomy? The higher-order systems, or executive functions, required for performing dual tasks generally involve the frontal lobe. Serrien, Ivry, and Swinnen (2007) indicated that the areas of the brain associated with cognitive processes may also be implicated in motor involvement. Regardless of whether research encompasses healthy individuals participating in dual tasks with increased task complexity, or individuals with neuropathology, the neural correlates suggest that the frontal lobe is important for both cognitive functioning as well as the organization of motor skills (Serrien et al., 2007).

In addition, McCulloch (2007) indicated that the allocation of resources, specifically that of attention, is also considered a task of executive functioning. Therefore, for individuals with frontal lobe damage, or impaired executive functioning, dual tasks may be more difficult due to reduced attentional resources. Furthermore, for patients with neuropathology, tasks that were simple or automatic prior to injury or pathology may demand more attention afterward and may also be more difficult. McCulloch (2007) also states that the dual-task paradigm is related to real life in that people often attend to and combine more than one type of stimulus at a time (i.e. talking to a friend while walking).

A number of virtual reality studies have been conducted using a variety of populations including healthy undergraduate students (Law, Logie, & Pearson, 2006), individuals that have experienced a stroke (Kizony, Levin, Hughey, Perez, & Fuung, 2010; You et al., 2005), and traumatic brain injury (see Rose, Brooks, & Rizzo, 2005 for a review). Law and colleagues (2006) conducted a study in which 42 undergraduate students completed a task in a virtual environment in which they were required to engage in multitasking to complete a number of errands in a specified amount of time. Two different verbal interference tasks were used as part of the dual-task paradigm: one in which random generation of months was necessary and another in which one month was repeated throughout the task. Results indicated that under the dual-task condition, performance in both groups declined, with the group that was required to randomly generate months of the year demonstrating a more pronounced decrease in performance (Law et al., 2006). These researchers demonstrated that the dual-task paradigm is feasible using a virtual environment with healthy individuals; how does this virtual setting compare to the patient population?

Kizony and colleagues (2010) compared gait performance of 12 patients with stroke to 10 age-matched older adults in a virtual environment which simulated a grocery store. Participants walked on a self-paced treadmill and held on to the railing in front of them to simulate pushing a shopping cart as they walked through the aisles and shopped for specific items. The researchers found results inconsistent with other studies in that overall, participants tended to increase gait speed and the length of their stride during the dual-task portion of the study. However, the authors postulated that their inconsistent results may have been due to a variety of reasons such as shopping being a familiar activity, walking on a treadmill as a novel task in itself, inadvertent prioritization of tasks by the participants, or lack of secondary task difficulty.

Likewise, You and colleagues (2005) studied individuals with stroke, with a particular interest in examining cortical reorganization during a rehabilitation intervention utilizing virtual reality. Unlike other studies, these researchers used random assignment of 10 individuals with stroke to either a control condition that did not receive intervention, or the experimental group that was provided with a virtual reality intervention for 60 minutes per day, five times per week, for a four-week period. In addition, the researchers used fMRI to examine cortical activity. Overall, results indicated that the motor scores for the virtual reality group were significantly better than the control group. Of the cortical areas examined, only the primary sensorimotor cortex yielded a statistically significant laterality index, indicating that a shift in hemispheric dominance was present as a result of the intervention. Prior to intervention, the researchers found cortical activation to be ipsilateral to the leg performing the movement; however, after the virtual reality intervention, they found activation that was contralateral, and comparable to normal subjects. Participants who demonstrated cortical reorganization also displayed a considerable increase in locomotor ability. Therefore, the authors indicate that their results suggest that virtual reality intervention may be able to stimulate reorganization of the motor pathways in the cortex (You et al., 2005). The previously discussed research not only provides evidence of the feasibility of virtual reality interventions, but preliminary data to support its benefits.

Rose and colleagues (2005) review a number of virtual reality studies that generally focused on assessment and rehabilitation of different aspects of cognition including executive functioning, memory, spatial abilities, attention, and visual neglect in individuals with brain injuries. These studies tended to concentrate mainly on assessment of these domains of impairment and the feasibility of rehabilitation programs using virtual reality compared to that of traditional rehabilitation methods.

There have been few studies that have examined whether motor learning in the neurologically impaired population occurs the same way as in healthy individuals. The relationship between the two is not well understood (Cirstea, Ptito, & Levin, 2003; Winstein, Merians, & Sullivan, 1999). However, Winstein and colleagues (1999) examined this concept in 40 patients with stroke (20 with right hemisphere damage and 20 with left hemisphere damage) as compared to 40 healthy individuals. Participants were to perform a specific motor task while in the seated position. The researchers found that with practice, both groups demonstrated improvement. Additionally, the researchers found no differences between groups regarding forgetting and savings, indicating that the level of absolute ability for motor learning is the same in patients and healthy controls (Winstein et al., 1999). In contrast, Cirstea and colleagues (2003) investigated whether a group of 20 patients who have experienced a stroke improve in the same way as 10 healthy controls. Motor impairment was assessed by comparing arm reaching in the two groups. Although results demonstrated improvements for both groups after just one practice session, the patients with stroke displayed arm movements that were slower and less precise as well as more segmented. In addition, the researchers found that the patients with stroke required many more repetitions in order to demonstrate changes compared to healthy individuals (e.g., 55 versus 20; Cirstea et al., 2003).

The previous two studies have demonstrated varying aspects of motor learning and control in patients with stroke. Winstein and colleagues (1999) demonstrated that while the quality of the movement may be affected, a patient's capacity for motor learning remains intact; Cirstea and colleagues (2003) demonstrated that patients are able to learn novel motor skills, but may require more trials to observe similar improvement. Although several studies have provided plots of the data regarding performance measures, the majority of the literature focuses on whether or not there were significant group differences. However, the specific aspects of overall performance and rate of learning have not been closely examined. In addition, although there has been some research regarding individuals with Parkinson's disease (Onla-Or & Winstein, 2008; Nieuwboer, Rochester, Muncks, & Swinnen, 2009) and TBI (Katz-Leurer, Rotem, Keren, & Meyer, 2011), the literature largely focuses on individuals with stroke.

Although these previously discussed studies have demonstrated differential effects within the stroke population, it is unknown whether these results can generalize to the TBI population; therefore, additional research is needed in order to determine whether these findings can be applied to individuals who have experienced a TBI. The current study utilized virtual reality simulations to examine general movement and learning in individuals who have experienced varying degrees of TBIs. The design of the study allowed researchers to take an exploratory approach in order to determine how cognitive deficits caused by brain damage affect the learning process with regard to motor learning. In other words, do people with brain injuries learn the same as healthy individuals, or are there specific components that are different between the two groups that inhibit those with brain injuries from motor learning? The current study examined how cognition influences an individual's ability to learn novel motor tasks. A control group of healthy individuals and an experimental group of individuals with TBI were assessed using neuropsychological tests measuring a variety of areas including verbal memory, visual memory, processing speed, executive functioning, motor abilities, premorbid functioning, working memory, and visuospatial abilities. Specific points of interest from the virtual reality simulations included the rate of learning and the overall performance of each participant.

Based on the previously discussed findings, it was hypothesized that the control group would demonstrate a higher level of performance than the TBI group. In addition, it was also hypothesized that although both groups would demonstrate learning across trials, the control group would learn at a faster rate than the TBI group. Because the purpose of the virtual reality simulation is to measure varying aspects of motor functioning, it was hypothesized that the neuropsychological test scores regarding motor abilities (Finger Tapping and Grooved Pegs) would be most highly correlated with motor scores from the simulation. Considering the requirements of the virtual reality task itself, it was also hypothesized that measures of visual memory (WMS VR-I, VR-II) and visuospatial abilities (MVPT, ROCF) would be highly correlated with motor functioning as well. The dual-task research has emphasized the importance of executive functions in the allocation of resources; however, it was hypothesized that there would not be a significant association between motor functioning and executive functions because it is unlikely that the virtual reality simulation would be cognitively challenging enough to tax executive functions to produce the effect that a dual-task paradigm yields.

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