Cognitive ability predicts motor learning on a virtual reality game in patients with TBI

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Abstract

BACKGROUND: Virtual reality games and simulations have been utilized successfully for motor rehabilitation of individuals with traumatic brain injury (TBI). Little is known, however, how TBI-related cognitive decline affects learning of motor tasks in virtual environments.

OBJECTIVE: To fill this gap, we examined learning within a virtual reality game involving various reaching motions in 14 patients with TBI and 15 healthy individuals with different cognitive abilities.

METHODS: All participants practiced ten 90-second gaming trials to assess various aspects of motor learning. Cognitive abilities were assessed with a battery of tests including measures of memory, executive functioning, and visuospatial ability.

RESULTS: Overall, participants with TBI showed both reduced performance and a slower learning rate in the virtual reality game compared to healthy individuals. Numerous correlations between overall performance and several of the cognitive ability domains were revealed for both the patient and control groups, with the best predictor being overall cognitive ability.

CONCLUSIONS: The results may provide a starting point for rehabilitation programs regarding which cognitive domains interact with motor learning.

Keywords: Cognitive ability, virtual reality, traumatic brain injury

1. Introduction

Application of virtual reality games for motor rehabilitation of individuals with acquired brain injury has received considerable interest over past decades (Cherniak, 2011; Holden, 2005; Mumford & Wilson, 2009). Practice in safe and motivating virtual environments allows relearning of motor and functional skills, thereby facilitating recovery across several domains (Flanagan et al., 2008; Schultheis et al., 2002). Studies applying virtual reality games and simulations reported improvements of static and dynamic postural stability (Suárez et al., 2006); gait (Batson et al., 2011); cognitive abilities (Rose et al., 2005); abilities to perform ADL (Flanagan et al., 2008; Matheis et al., 2007; Schultheis et al., 2002; Zhang et al., 2003), and fine arm movements (Cirstea et al., 2003; Rand et al., 2005) in patients with brain injury. While noticing a facilitatory effect of virtual environments, authors also agreed that recovery after brain damage requires motor learning (Holden, 2005; Sullivan, 2007; Wulf et al., 2010). Motor learning can be defined as an internal process that results in a relatively permanent change in an individual’s capability to perform a motor task (Kern, 1982; Magill, 2004; Schmidt & Wrisberg, 2004). The mechanisms underlying motor learning in intact nervous system may not necessarily be the same in individuals with brain injury (Levin, 2011). Brain damage

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often affects cognitive processes, such as attention and executive function, as well as working memory (Rose et al., 2005). All of these functions are important for re-learning motor functions, lost as result of the brain injury (Dikmen et al., 2009; Eslinger et al., 2007; Robinson-Riegler & Robinson-Riegler, 2004). Very little is known about the impact of cognitive decline on the dynamic of motor learning. A few studies, including a recent meta-analysis found that dual-task paradigms require the use of higher-order cognitive systems that, in turn, influence gait control. The researchers found that these cognitive tasks influenced many aspects of motor functioning including slower performance, a decrease in cadence, and increases in stride length, stride time, and stride time variability (Al-Yahya et al., 2011; Catena et al., 2007, 2009; Holtzer et al., 2006; Sosnoff et al., 2008). These studies reflect the importance of examining the role of cognitive functioning in motor performance.

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. Although studies have demonstrated differential effects within people with stroke (Cirstea et al., 2003; Weinstein et al., 1999), it is unknown whether these results generalize to people with a history of TBI. Investigation of this question is important to promote development of novel rehabilitation techniques, including virtual reality games and environments for patients with 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.

Overall, the goal of this study was to determine cognitive predictors of motor performance and learning in the virtual environment. 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. It was hypothesized that the TBI group would demonstrate a decreased level of motor performance and slower rate of learning than the control group due to cognitive deficits. 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.

2. Method

2.1. Participants

Participants included 15 individuals with a history of TBI (TBI group; 7 male, 8 females), mean age of 32.5 (SD = 9.44; range 18–44), and a control group that consisted of 15 healthy individuals (control group, 7 male, 8 females), mean age of 33.40 (SD = 9.67; range 18–47). The TBI participants were recruited through a variety of sources including advertisements in local newspapers and newsletters as well as advertising during support groups. 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 age. Therefore, the final analyses included a total of 14 patients. Of the 14 patients, nine reported being in a coma, with the average length of time being 29.48 days (SD = 26.42, range 33–90 days), one person reported experiencing a loss of consciousness for <30 minutes. One patient was unsure of loss of consciousness, and three denied experiencing loss of consciousness or coma. The average time since injury was 10 years (SD = 8.01, range 5.0–22.33 years).

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 signed an informed consent form that was prepared in compliance with the Declaration of Helsinki and approved by the Institutional Review Board.

2.2. Gaming system

The gaming system consisted of a Dell Mobile Precision M6600 laptop (Intel i7 quad core CPU) with a graphics accelerator (NvidiaQuadro FX 3800M) integrated with a 6-camera system for motion capture (Qualisys AB, Sweden). Participant interaction with the simulated virtual environment occurred via hand avatars, precisely reproducing the real-time kinematic patterns. The avatars were created with 3 reflective
markers (12 mm in diameter) attached to each hand. The movements of the markers were recorded by the Qualisys system for motion analysis at 100 Hz and then synchronized with the VR gaming scenario with minimum delay. The image was projected in 3D format onto an 80-inch screen (1080p Mitsubishi DLP® TV bundle, RealD) and was viewed by the participant in the first-person view via shutter glasses (RealD Professional CrystalEyes 5; Fig. 1). The glasses are emitter free and thereby caused no interference with the infrared signal emitted by the motion capture system. Wearing these light weight glasses (67 grams) posed minimum constraint on participants’ movements. The gaming scenario was developed using WorldViz’s Vizard software (WorldViz LLC) with computer graphics created with Alias’ Maya package for 3D animation (Maya®, Version 7.0.1; Autodesk, Inc.).

2.3. Neuropsychological testing

Verbal Memory was assessed by the California Verbal Learning Test – Second Edition (CVLT-II; Delis et al., 2000). Participants were read a list of words and were required to recall as many of the words as possible immediately and after a delay. Additionally, the CVLT-II has cued recall trials, an interference list, and a recognition portion. Raw scores and standard scores (reported as z-scores) are provided for the immediate recall trials, short delay, and long delay trials for both free recall and cued recall sections.

Visual Memory was assessed by the Visual Reproduction I and II subtests of the Wechsler Memory Scale–Fourth Edition (WMS-IV: VR-I, VR-II; Wechsler, 2009a). Visual Reproduction (VR) is part of the WMS-IV and consists of two primary subtests: VR-I and VR-II. Scores for VR-I and VR-II are based on a scoring rubric for each of four 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.

Processing Speed was assessed by several measures including the Symbol Digit Modalities Test (SDMT; Smith, 1991), Trails 1, 2, and 3 from the Delis-Kaplan Executive Function System (D-KEFS Trails; Delis et al., 2001a), and Basic Color Naming and Word Reading from the Delis-Kaplan Executive Function System (D-KEFS Color-Word Interference Test; Delis et al., 2001a). 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. A single z-score is provided for both the written and oral forms. 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 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. The Color-Word Interference Test consists of three total conditions. The first two conditions measure processing speed: Basic Color Naming and Word Reading. Raw scores reflect how quickly the participant is able to name each color or read each word, depending on the condition; these scores are converted to scaled scores (range 1–19) based on the person’s age.

Executive Functioning was also assessed by several measures including Trails 4 from the Delis-Kaplan Executive Function System (D-KEFS Trails; Delis et al., 2001a), Inhibition from the Delis-Kaplan Executive Function System (D-KEFS Color-Word; Delis et al., 2001a), and the Controlled Oral Word Association Test (COWAT; Benton & Hamsher, 1976). 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 et al., 2001b). The third condition of the Color-Word
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.

Working Memory was assessed by the Digit Span subtest of the Wechsler Adult Intelligence Scale–Fourth Edition (WAIS-IV: Digit Span; Wechsler, 2008a) and the Symbol Span subtest of the WMS-IV (WMS-IV: Symbol Span; Wechsler, 2009a). 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. Raw scores (number correctly recalled) and scaled scores (based on age of participant) are provided for the total and each section. 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. 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).

Visuospatial Abilities were assessed by the Motor-Free Visual Perception Test – Third Edition (MVPT-3; Colarusso & Hammill, 2003) and the Rey-Osterreith Complex Figure: Copy Trial (ROCF Copy; Meyers & Meyers, 1995). 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. Rey-Osterreith Complex Figure: Copy Trial (ROCF Copy; Meyers & Meyers, 1995). During the ROCF Copy Trial, participants are required to copy an abstract figure from the stimulus card onto a blank sheet of paper. 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.

3. Procedure

3.1. Virtual reality game

Participants practiced the “Octopus” game 10 times during the session. Each 90-s game included ∼20–25 reach-to-pop movements, with a total of 200–250 repetitions per session. The objective of the game was to pop as many of the bubbles as possible by reaching out with the left or right hand; each bubble popped earned participants a point. To avoid fatigue, a 1–2 min rest period (in standing or sitting position) was allowed between trials. A retention test of 2 gaming trials was administered 30 min after the end of the practice. The 2 retention trials repeated the first and last gaming scenario of the practice session, with the scores averaged. Before the session began, a single game trial was introduced to participants to familiarize them with the game content and thereby to reduce a warm up effect. On average, each gaming session lasted for ∼1 h, including time for the practice itself and rest.

3.2. Data collection and analysis

Data collection included information from both the virtual reality game and the neuropsychological testing. The virtual reality game provided information regarding participants’ motor skills and learning. On each of the ten 90-second trials the total number of points was calculated to create a performance score for that trial. Motor learning was separated into two phases: early stage learning consisted of trials 1–3 and late stage learning consisted of trials 8–10. Overall learning for each stage was calculated by averaging the number of points earned on the three trials. Rate of learning was determined by calculating the best-fit regression line using the three performance trials from the virtual reality game the respective stage and for each individual participant.

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.

Statistical analyses were conducted based on the two stages of motor learning. First, group differences on the virtual reality game and the neuropsychological test measures were examined using independent samples t-tests. Paired t-tests were used to analyze learning across trials for each group. Additionally, Cohen’s d was used as a measure of effect size to examine the difference in magnitude between groups regarding neuropsychological test scores. Correlations were performed to examine the relationship between neuropsychological test measures and performance and rate of learning during both stages of motor learning. Regression analyses were also conducted to determine predictors of motor learning.

4. Results

4.1. Sample characteristics

Correlations with time since injury were examined 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 four motor variables from the virtual reality task. Therefore, it was not included in the remainder of analyses.

With regard to motor functioning, participants in the TBI group presented with different severities of post-injury impairments and functional limitations, which were evaluated by experienced clinicians via a battery of clinical tests (Table 1). The Ataxia Test by Klockgether (Klockgether et al., 1990) rates ataxia of gait, stance, upper and lower extremities, dysdiadochokinesia, intention tremor, and dysarthria on a 6-point scale, with 0 points indicating no symptoms and 5 points indicating the most severe symptom manifestations in each testing category. A total score of 1–7 points corresponds to mild ataxia, 8–21 points to moderate ataxia, and >21 severe ataxia. Patients’ scores were indicative of mild to moderate ataxia. The Berg Balance test (BBS; Berg et al., 1998) ranges from 0–56, with a score of 45 points on the BBS indicating a high fall risk. Patients had scores

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Summary of motor and functional testing for TBI group</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBI</td>
<td>Ataxia test</td>
</tr>
<tr>
<td>Mean</td>
<td>7.79</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>4.48</td>
</tr>
<tr>
<td>Range</td>
<td>3–19</td>
</tr>
</tbody>
</table>

Note. N = 14.
ranging from 39 to 56 points on the Berg Balance test. The Functional Gait Assessment Test (FGA; Wrisley et al., 2004) ranges from 0–30, with a score of 22 points indicating a high fall risk. Patients showed a mean gait performance of 21.57 on the FGA. Overall, according to clinical scales, 6 participants had mild and 8 other patients had moderate functional and motor deficits. Participants showed nearly full ranges of motion and nearly normal muscle strengths in the major muscle groups.

4.2. Group differences on the virtual reality task

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). Separate calculations were performed for each participant for both stages of motor learning. The control group’s performance was significantly higher than the TBI group for both early and late stage performance, *t* (27) = 4.38, *p* < .001; *t* (27) = 4.41, *p* < .001, respectively, suggesting that the control group was capable of performing at a higher level than patients.

Additionally, the control group’s rate of learning in the early stage was significantly faster than the TBI group, *t* (27) = 2.91, *p* < .01; however, this difference was not sustained in the late stage of learning, *t* (27) = 0.63, *p* = .534. Results from paired t-tests comparing performance on the first and last trials showed that both groups demonstrated significant improvement across trials, *t* (14) = 4.26, *p* = .001 for controls, and *t* (13) = 2.83, *p* = .014 for patients. These findings suggest that although both groups maintained positive slopes, the control group made greater gains early on compared to the TBI group. Figure 2 visually displays both groups’ overall results from the virtual reality portion of the study; additionally, Figs. 3 and 4 display each group’s performance during each stage of the game. Using an F-test to compare standard deviations for each group, results indicated that patients displayed significantly more variability in virtual reality scores than healthy controls (*F* = 3.11, *p* = .042).

4.3. Group differences on neuropsychological test measures

4.3.1. Performance

Descriptive statistics for neuropsychological tests and significant group differences are shown in Table 3.

![Fig. 2. Performance by group.](attachment:image)
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. 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.

The control group consistently performed better than the patient group, with each measure in all eight cognitive domains demonstrating significant differences between groups. Patient performance ranged from low average to severe impairment on a variety of measures.

4.3.2. Correlations

Given the small sample size, statistical significance may be less interesting than moderate to strong correlations, even if these relationships did not reach statistical
medium to large effect sizes during both stages of motor learning. However, the remaining composite scores had fewer associations; only the Visual Memory Composite score had a moderate effect size with early stage learning.

Correlations between rate of learning and neuropsychological measures produced a different pattern of results. For the patient group, the only significant correlation was between Premorbid Functioning and rate of learning during the late stage. However, several of the other composite scores were moderately correlated with early stage rate of learning including Verbal Memory, Processing Speed, Executive Functioning, Motor Abilities, Visuospatial Abilities, and Working Memory. During the late stage of motor learning, aside from Premorbid Functioning, only the Motor Abilities were significantly correlated with the rate of learning.
ties, Visual Memory, and Working Memory Composite scores remained moderately correlated with rate of learning. All associations were positive.

In the control group, only the Verbal Memory and Processing Speed Composite scores were significantly positively related with rate of learning during the early stage. Executive Functioning, Motor Abilities, Premorbid Functioning, and Working Memory were all positively associated with early stage rate of learning and demonstrated moderate effect sizes. Although no longer significant, Verbal Memory and Processing Speed remained positively associated with late stage rate of learning and had moderate effect sizes. Additionally, the Visual Memory Composite score demonstrated a negative association with late stage rate of learning and had a fairly large effect size.

### 4.3.3. Composite score correlations

The composite scores were correlated with each other in order to determine if multicollinearity may be an issue in regression 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.

### 4.4. Regression analysis

Because all of the eight cognitive domains were significantly related to one another in the patient group,
Table 6: Correlations among cognitive composite domains for the patient group

<table>
<thead>
<tr>
<th>Composite domain</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal memory</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processing speed</td>
<td>773**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Executive function</td>
<td>699**</td>
<td>957**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor abilities</td>
<td>690**</td>
<td>761**</td>
<td>726**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Premorbid functioning</td>
<td>633*</td>
<td>522</td>
<td>539*</td>
<td>485</td>
<td>1</td>
<td></td>
<td></td>
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<tr>
<td>Working memory</td>
<td>870**</td>
<td>878**</td>
<td>836**</td>
<td>691**</td>
<td>701**</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visuospatial abilities</td>
<td>810**</td>
<td>854**</td>
<td>828**</td>
<td>709**</td>
<td>606*</td>
<td>594**</td>
<td>1</td>
<td></td>
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<tr>
<td>Visual memory</td>
<td>648*</td>
<td>673**</td>
<td>636*</td>
<td>765**</td>
<td>639**</td>
<td>695**</td>
<td>628**</td>
<td>1</td>
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</tbody>
</table>

Note: n = 14. *p < .05, **p ≤ .01.

Table 7: Correlations among cognitive composite domains for the control group

<table>
<thead>
<tr>
<th>Composite domain</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<tbody>
<tr>
<td>Verbal memory</td>
<td>1</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Processing speed</td>
<td>.706**</td>
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<td></td>
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<tr>
<td>Executive function</td>
<td>.592*</td>
<td>.624*</td>
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<tr>
<td>Motor abilities</td>
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<td>.430</td>
<td>.373</td>
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<td>Premorbid functioning</td>
<td>.191</td>
<td>.194</td>
<td>.275</td>
<td>.226</td>
<td>1</td>
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<td>Working memory</td>
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<td>.660**</td>
<td>.070</td>
<td>.377</td>
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<td>Visuospatial abilities</td>
<td>−.190</td>
<td>−.232</td>
<td>.042</td>
<td>.310</td>
<td>.410</td>
<td>.097</td>
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<td>Visual memory</td>
<td>.257</td>
<td>.233</td>
<td>.342</td>
<td>.280</td>
<td>.173</td>
<td>.167</td>
<td>249</td>
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Note: n = 15. *p < .05, **p < .01.

Table 8: Hierarchical regression analysis for variables predicting rate of learning during the early stage of learning

<table>
<thead>
<tr>
<th>Variable</th>
<th>F</th>
<th>ΔF</th>
<th>R</th>
<th>ΔR²</th>
<th>B</th>
<th>SE B</th>
<th>β</th>
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<td>TBI Group</td>
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<td>Step 1 demographic variables</td>
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<td>.109</td>
<td>.115</td>
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<tr>
<td>Gender</td>
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<td>Step 2 demographic variables</td>
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<tr>
<td>Global ability index</td>
<td>2.459</td>
<td>3.10</td>
<td>.425</td>
<td>.315*</td>
<td>2.144</td>
<td>916</td>
<td>.417*</td>
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<td>Global ability index</td>
<td>2.415</td>
<td>3.11</td>
<td>.397</td>
<td>.331*</td>
<td>5.543</td>
<td>2.235</td>
<td>.579*</td>
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Note: n = 15 for the Control Group and 14 for the TBI Group. F = unstandardized regression coefficient, ΔF = standard error of F, R² = standardized regression coefficient. *p < .05, **p < .01.

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 performance and rate of learning during the early and late stages of the game for each group. Demographic variables including gender and age were entered in the first block, and the Global Ability Index was entered in the second block. Dependent variables were separated by early and late stage for both performance and rate of learning. Results of the hierarchical regression analysis for variables predicting rate of learning during the early stage
of learning are shown in Table 8. With regard to rate of learning, neither of the demographic variables were significant predictors for the controls or TBI group. The Global Ability Index was a significant predictor of rate of learning during the early stage for both groups. In the TBI group, the Global Ability Index explained 31.5% of variance over and above the demographic variables, which was statistically significant. In the control group, the Global Ability Index added 33.1% of variance over and above the demographic variables, which was also statistically significant.

Next, the same hierarchical regression analysis was performed to examine participants’ rate of learning during the late stage of learning. Demographic variables explained 51.9% of the variance for the control group, which was significant, $R^2 = .519$, $F(2,12) = 6.469$, $p = .012$; however neither demographic variables was a significant predictor of rate of learning in the late stage for the TBI group.

None of the variables were significant predictors of absolute level performance in either stage for either group.

5. 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 determine cognitive predictors of motor performance and learning in a virtual environment. Results showed superior performance of the control group relative to the TBI group on both the virtual reality game and the neuropsychological testing. Control participants’ rate of learning was significantly faster than the TBI patients’ during the early phase, but did not differ during the late phase.

Measures of executive functioning, visual memory, and visuospatial abilities were significant predictors of performance in both early and late stages of learning for the TBI group.

Consistent with hypotheses, the control group exhibited a higher level of overall performance than the TBI group across both stages of learning during the virtual reality game. 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. 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 TBI group displayed significantly more variability in virtual reality scores than healthy controls.

It was hypothesized that both the TBI and control group would exhibit learning across trials, but that the control group would learn at a faster rate. Current findings partially supported this hypothesis. When examining the results based on early and late stages of learning, the control group’s rate of learning in the early stage was significantly faster than the TBI group, but rate of learning did not differ in the late stage. These findings may be confounded by task difficulty, as both groups reached their maximum potential prior to the final trial, leaving minimal opportunity for additional learning. Thus, there may not have been the opportunity for control participants to demonstrate learning rates at the later stages. Other researchers have found a similar pattern on relatively simple motor tasks (Catena et al., 2007, 2009).

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 game for the patients and healthy controls.

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 than other cognitive measures in the virtual reality game in both groups. Results of individual test measures support this hypothesis regarding the latter two domains for the TBI group. Measures of visual memory and visuospatial abilities were significant predictors of performance in both early and late stages of learning. It seems logical that measures of visual memory and visuospatial abilities would be the most highly correlated with performance because of the overall requirements of the virtual reality game; participants were required to reach out into space to pop bubbles (a task, by definition, associated with visuospatial abilities) and become accustomed to the task over the ten trials, which required them to remember the visual stimuli. The fact that these relationships were not seen in the healthy group may have been influenced by task difficulty. Healthy individuals were able to engage in the virtual reality game with little difficulty, suggesting that these motor movements occurred rather automatically. Because patients with brain damage are believed to have depleted cognitive resources, the task was more of a challenge and thus less automatic.
With regard to motor functioning, this hypothesis was only partially supported. In the TBI group, Motor Abilities as a whole demonstrated a medium effect size during both stages. Measures of processing speed were associated with performance during both stages for the TBI group. Contrary to hypotheses, executive functioning also showed a relationship with performance for the TBI group. Whereas previous research did not find an association with executive functioning due to task difficulty, it may have been that this novel virtual reality game did in fact tax patients’ cognitive abilities and thus were required to engage in higher-order thinking in order to complete the task.

As patients learned the virtual reality game, correlations between neuropsychological test measures and their virtual reality performance tended to decrease across domains. 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. Furthermore, this Global Ability Index significantly predicted rate of learning during the early stage of motor learning for both groups, suggesting cognition was related to motor functioning.

5.1. Limitations

The current study has several limitations. The patient and control groups had 29 combined participants, limiting the power to detect small effects. 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 et al., 2007; Cirstea et al., 2003). Patient screening did not include a thorough medical background; therefore, the location of brain damage was unknown.

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 develop 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.

6. 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 range to control for confounding effects.

Acknowledgement

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Declaration of interest

The authors declare no conflicts of interest.

References


obtained with the functional gait assessment. *Journal of the American Physical Therapy Association, 84* (10), 906-918.

