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ABSTRACT

This study investigated the design of a virtual reality (VR) simulation integrating a haptic control interface for motor skill training. Twenty-four healthy participants were tested and trained in standardized psychomotor control tasks using native and VR forms with their non-dominant hands in order to identify VR design features that might serve to accelerate motor learning. The study was also intended to make preliminary observations on the degree of specific motor skill development that can be achieved with a VR-based haptic simulation. Results revealed

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significant improvements in test performance following training for the VR with augmented haptic features with insignificant findings for the native task and VR with basic haptic features. Although performance during training was consistently better with the native task, a correspondence between the VR training and test task interfaces lead to the greater improvement in test performance as reported by a difference between baseline and post-test scores. These findings support use of VR-based haptic simulations of standardized psychomotor tests for motor skill training, including visual and haptic enhancements for effective pattern recognition and discrete movement of objects. The results may serve as an applicable guide for design of future haptic VR features.

KEYWORDS

Haptic simulation, virtual reality, neuropsychological tests, Rey-Osterrieth Complex Figure, Block Design

INTRODUCTION

The capabilities of virtual reality (VR) systems to present stereoscopic displays, to render virtual surface models and to provide haptic force-feedback for users from virtual objects make the technology a prime candidate for motor skill training. VR systems can be developed to replicate key aspects of real-world tasks for repeated training trials. In this way, systems can reduce real training task costs as well as trainer workload. However, VR can also add a countless array of augmented controls and decision features to simulations to aid user performance that would be difficult to implement in a physical system. Such features include omnidirectional force

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resistance in a haptic interface, precise corrective forces for hand motion, and enhanced visual aids that respond to user actions.

Previous research on VR-based haptic simulation has demonstrated system efficacy as a therapeutic tool for motor function rehabilitation (Merians, 2002; Ku et al., 2003; Wiederhold & Wiederhold, 2004; Jang et al., 2005; You et al., 2005; Holden, 2005; Holden et al., 2007). However, additional investigation is needed to determine how to implement combinations of augmented features that may provide therapeutic benefits over traditional systems. In the present study, we sought to expand on the existing research by identifying specific VR design features that might serve to accelerate motor learning beyond basic VR and native forms of training tasks. We also made preliminary observations on the degree of skill development that can be achieved with a VR-based haptic simulation by testing and training healthy participant psychomotor control in native and VR forms of standardized psychomotor tasks when participants used their non-dominant limbs (in order to ensure learning potential).

In general, our experiment design replicated a simplified occupational therapy regimen. A drawing and pattern assembly task represented an occupational task that was anticipated to improve as a result of therapy. These types of tasks incorporate fundamental motions and sequences that occur in many work or daily living activities (e.g., writing) that are of interest to occupational therapy practitioners (Yancosek & Mullineaux 2011). Specifically, we identified the Rey-Osterrieth Complex Figure (ROCF; Osterrieth, 1944; Rey, 1941) test to represent the occupational task. The ROCF requires participants to accurately reproduce a single picture composed of 18 shapes and patterns (Figure 1 (a)). It is a common diagnosis tool used in many

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medical centers to evaluate different psychomotor functions, such as perceptual apprehension, visual construction, attention, planning, and spatial memory (Bennett-Levy, 1984; Hamby et al., 1993; Osterrieth, 1944). Representing a surrogate occupational task, the ROCF was administered once prior to training to evaluate baseline psychomotor performance and again following multiple psychomotor training sessions in order to measure performance improvements.

For participant motor training as part of the experiment, we developed a separate VR task to be used in a course of therapy. Based on a motion analysis of ROCF control actions, we observed that a block placement or assembly task requiring planning and fine motor control of objects included many control features common to a complex drawing task. As a result, the research team designed and developed a VR reproduction of the block design (BD) subtest from the Wechsler Abbreviated Scale for Intelligence (WASI: The Psychological Corporation, 1999) for participant training purposes. The present study represents the design, development and first empirical investigation using the VR-BD task.

Insert Figure 1 about here

The BD subtest evaluates visuospatial and motor skills by requiring participants to build replicas of patterns using identical blocks. Participants are given a collection of nine red and white cubes with varying patterns on each side and are asked to replicate the designs shown on a series of test cards (Figure 1 (b)). Scoring is based on speed and accuracy. The BD test can be categorized as a spatial recognition task (Rauscher et al., 1997) because scores are primarily influenced by spatial visualization ability and motor skills. There is a physical model present to be copied, and therefore does not require formation of an internal mental image. Hoffman et al. (2003) suggested that successful BD construction requires the observer to:

1. visually encode parts of the model and their spatial organization,
2. select among candidate blocks to determine which to use,
3. check against the model to determine the block's location,
4. place the block in the work area, and
5. recheck to be sure that the block has been placed in the correct location.

Lee et al. (2009) stated that the process involved in copying an image, such as the ROCF, could be very similar. Both tests require participants to be able to perceptually analyze the parts of an array and then replicate the global configuration. ROCF and the BD scores have also been shown to be moderately correlated due to their common reliance on a "visuospatial perceptual/memory factor" (Spreen & Strauss, 1998) and constructional praxis. For these reasons, we expected the ROCF scores would corroborate differences in performance on the BD task.

In addition to developing a VR version of the WASI BD task, an augmented version was developed featuring visual aiding and haptic guidance using virtual fixtures. Virtual fixtures are a

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form a penalty-based haptic feedback that help the user maintain a desired course by activating in response to errors (Rosenberg, 1993). There are numerous options for implementing virtual fixtures. For example, Basdogan et al. (2007) combined multiple haptic features for a system providing haptic assistance to control optical tweezers during an assembly task. The researchers provided feedback forces in the form of virtual fixtures to help participants move microparticles along optimized trajectories. The specific forces presented to users through the haptic device included: (1) penalty-based guidance forces to keep users on an optimal path, (2) a drag force when users moved too fast, and (3) a snap effect to indicate the end of the path. The snap effect completed the movement by pulling the particle into the target when it was within close range. The results showed improvements in the average path error and average speed by combining haptic and visual feedback during task performance, as compared with visual feedback only.

Virtual fixtures have also been used in virtual environments for training applications. Lee et al. (2009) implemented different forms of virtual fixtures to help train people with Williams Syndrome (WS) drawing pre-defined lines to construct simple shapes. The haptic device automatically applied corrective forces proportional to the magnitude of the error in response to deviations from correct drawing paths. Their results showed that haptic training did improve immediate copying ability in young children and adults with WS. The researchers speculated that the constant feedback provided by the virtual fixtures may have reminded the operators to check their progress against a model, which increased the number of times participants verified their responses and improved accuracy.

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Although virtual fixtures help during task performance (Basdogan et al., 2007), the aftereffects have been shown to last for relatively short periods and as a result have not demonstrated their effectiveness for long-term training (see Milot, Marchal-Crespo, Green, Cramer & Reinkensmeyer (2010) and Patton & Mussalvaldi (2004) for reviews). One explanation for this is that when virtual fixtures are present, users may learn to rely on their presence in the virtual training environment and, therefore, learn the environment in the context of the fixtures instead of the underlying task (Li, Huegel, Patoglu & O'Malley, 2009). In response to this issue, we sought to identify a balance of a sufficient level of haptic assistance that delegates some responsibility to the operator to promote learning but does not result in automation dependency. For the current work, this included the snap effect incorporated by Basdogan et al. (2007). This form of scheduled haptic feedback was intended to limit self-appraisals of performance to make operators less dependent on the haptic features for task performance.

The present study, involving healthy participants in use of their nondominant hand to simulate minor motor impairment, is a first step in a broader research effort to create a proof of concept of a VR system to be presented to individuals with a history of minor traumatic brain injury (mTBI) for motor skill rehabilitation. Simulations incorporating a VR environment allow for replication of visual aspects of tasks that are commonly used with those populations. The overarching goal of this research is to design and prototype custom VR and haptic interfaces for effective motor and visuo-perceptual reconstruction for persons seeking recovery from mTBI with motor control implications. Most studies investigating VR-based haptic simulation as a therapeutic tool have been conducted on stroke rehabilitation, with little information available on traumatic brain injury (TBI; Holden et al., 2001; Hillary et al., 2002; Laatsch et al., 2004; Strangeman et al.,

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2005) and how simulation requirements might differ relative to user condition. However, it has been observed that mTBI may have similar consequences to those of a stroke, including loss of motor skill (Harwin, Patton & Edgerton 2006), which provides motivation for introducing advanced rehabilitation technologies to patients with mTBI. As previously mentioned, the objective of the present study was to make preliminary observations on the degree of skill development that can be achieved by unimpaired participants with the VR-based haptic simulation design and to identify augmented features that might serve to accelerate psychomotor learning. The proof of concept is to be tested with mTBI patients in a future iteration of the experiment.

METHODS

Participants

Twenty-four participants between the ages of 18 and 44 were recruited for this study. All participants were required to have 20/20 or corrected to normal vision, and all were required to exhibit right-hand dominance. Right-hand dominance was identified through a demographic questionnaire and confirmed using the Edinburgh Handedness Inventory (Oldfield, 1971), both administered with electronic forms prior to a participant visiting the lab.

Apparatus

The software and hardware used in the experiment included separate platforms for the testing and training phases of the experiment. Psychomotor skill training (*BD training,* occurring

between baseline and post-testing) included multiple trials of the BD subtest from the WASI using the standardized test materials or the VR simulation of the WASI BD task, depending on the assigned condition. The post-testing to measure the training effects incorporated two commercially available psychomotor tests, including ROCF copy trials and the BD subtest from the Wechsler Adult Intelligence Scale – Third Edition (WAIS-III; Wechsler, 1997). The WAIS BD task used for testing and the WASI BD task procedures used for training are identical. Only the designs presented to participants are different. During testing, the WAIS BD subtests (*BD test*) were administered using standardized materials.

The ROCF was administered using a VR adaptation of the task developed in a previous study (Li et al., 2010). The ROCF interface was designed to replicate a drawing setup. It included a custom workstation featuring a flat-screen monitor mounted in a tabletop and an Omni Haptic Device (see Figure 2 (a)). To perform the ROCF, participants used the Omni to virtually draw the complex figure elements directly on the horizontally-aligned monitor while the simulation recorded participant performance data automatically. Rey Osterrieth Complex Figure performance is scored by evaluating 18 individual components of the figure that make up a complete design, referred to as units, on a scale from 0 to 2 in terms of accuracy (e.g., size, length) and placement (e.g., proximity to other units). The sum of the scores for the 18 components is calculated for a total score between 0 and 36. The VR interface for the BD training task (see Figure 2 (b)) was presented on a PC with a stereo monitor using a NVIDIA® 3D Vision™ Kit that includes 3D goggles and an emitter. The haptic control interface also incorporated an Omni haptic device.

Insert Figure 2 about here

Experiment Procedure

There were three main parts of the experiment for data collection: (1) an evaluation of pre-test (baseline) performance, (2) multiple training sessions, and (3) the post-test to measure improvement. Surrogate occupational and training tasks were represented by the ROCF and WAIS BD test tasks, respectively. The three parts of the experiment were distributed across four days, as presented in Table 1. Each participant committed a total of 5 hrs. to the study

Insert Table 1 about here

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Participants were randomly assigned to one of the three conditions. All participants were new to the VR environment and were required to use their non-dominant hands during baseline and post-test and training trials; that is, the experiment provided motor training to participants for the left hand. Limitations found in TBI patients, including impairment of motor skill, strength and coordination, as well as cognitive planning and memory use (Khan, Baguely & Cameron, 2003), have also been observed as physical and cognitive characteristics of non-dominant hand performance. Previous studies have found that disabled persons with motor control problems, such as limb coordination and balance, also have cognitive issues in terms of learning, attention and concentration (Barnes, 1999). Such impairment characteristics have been extensively demonstrated during the use of the non-dominant hand in motor skill training (Ozcan et al., 2004; Sainburg and Kalakanis, 2000; Yamashita, 2010), which further supports the cognitive requirements used in the study. The non-dominant hand requirement was also intended to disadvantage participant task performance in order to promote sensitivity to the training conditions.

All participants received the same orientation. They were initially familiarized with the haptic device and how to draw objects (lines, circles, a small house) using the ROCF drawing apparatus. Participants were permitted to practice with the device until they felt comfortable. This was followed by the baseline non-dominant hand performance evaluation using two ROCF

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copy tests and the WAIS-III BD test. During each training session, participants were required to complete multiple (2 or 3) WASI BD training trials. Each BD trial included a set of five 4-block designs and five 9-block designs; therefore, each subject manipulated a minimum of 520 blocks across the three training sessions. Training was facilitated through one of three representations of the task, either as a physical task (Native), a Basic VR task, or an Augmented VR task, including haptic aiding. Each participant was assigned to one task representation yielding a total of eight participants per condition. For their last session, participants were retested using the ROCF copy tests and the native WAIS BD test to identify any changes from baseline performance. For those participants assigned to either of the VR conditions, additional haptic device training was provided. Participants were shown how to click and grab a virtual block, how to move a block to a new location, and how to perform rotations. They were permitted to practice these subtasks until they felt comfortable. Participants were also instructed in how to complete a basic 2x2 block pattern in VR via demonstration and then permitted to practice in the pattern completion until they felt comfortable.

The 3-hour duration of the training was established through pilot testing prior to data collection. The results of the pilot test suggested that participants reached asymptotic performance after six BD training trials of 10 designs each. However, the experimenters also observed signs of fatigue (e.g., errors in completing designs that were previously completed correctly) after five consecutive trials. It was therefore decided that participants would complete multiple sessions with a limit on trials in order to mitigate fatigue effects. Participants who showed signs of fatigue during the final test session were allowed to complete the study, but their results were not included in the final analysis of the test data. As Table 1 shows, participants completed 2 BD

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training trials on the first day and 3 BD training trials on the second and third days of the experiment.

Experiment conditions

Table 2 summarizes the three conditions used in the study. Each participant was presented with only one of the conditions, and the number of participants was balanced across conditions. The nature of the conditions is described in the following sections.

Insert Table 2 about here

Condition 1: Native Task

This condition required participants to train using the Native WASI BD task. Administration of this condition used standard WASI test materials nearly identical to the procedures used during WAIS BD testing at baseline, except a different set of models was presented. Participants were also required to maintain a static grasp on each block. If a participant could not orient the block

using wrist motions and a static grasp, they were required to return it to the table and re-grip the block. The hand motions were constrained to cause some correspondence among the conditions in the experiment.

Condition 2: Basic VR

The Basic VR condition developed for this study featured a VR simulation of the WASI BD subtask. The goal of the simulation was the same as the Native BD training task. The VR features included a virtual tabletop divided into two parts: a work area and a display area. The display area presented the model depicting the design to be replicated by the participant. The work area was used for block assembly. The work area and blocks were presented at approximately 70% of actual size to allow the model and work area to be viewed on a 21-inch stereo monitor. The Basic VR task layout is shown in Figure 3 (a).

The Omni haptic device was used to manipulate a cursor appearing on the display. Participants could touch the cursor to a block and press a button on the stylus to "grab" the block. The blocks could then be lifted from the table's surface and rotated along any axis using the stylus. Participants were given up to 3 minutes to complete each BD training design. (It is important to note that the instructions for the native BD task also include a performance time limit; therefore, our approach to the experiment was driven by the original task administration.)

Some haptic features were included in the Basic VR to represent the blocks and the table. Blocks on the work surface were presented as solid objects and participants could feel a solid resistance

when a block touched the work surface. Participants could feel a similar resistance when touching the cursor to a block and when two blocks collided.

Condition 3: Augmented VR

The Augmented Haptic VR condition was identical to the Basic VR condition except for visual display and haptic enhancements designed to assist participants. The Augmented condition included a target grid for assembling the blocks (see Figure 3 (b)). All designs had to be constructed within the grid, which appeared as a 2x2 or 3x3 array of squares, depending on the design. Participants were provided assistive and corrective haptic forces during design assembly. The amount of force applied to the haptic stylus was calculated dynamically by an integrated software application based on control inputs to the device. If a participant attempted to place a block in an incorrect orientation in the grid, a resistive force equal and opposite to the pressure applied at the stylus prevented the block from touching the table. If a participant moved a block in the correct orientation over the grid, the participant would feel the block being pulled to the matching portion of the grid, by a snap force (as referenced above). The direction of the snap force was the vector from the stylus to the center of the matching portion of the grid, and the force ($F=kx$) was determined by the spring constant (k=0.5) and the distance (x) between the stylus and the matching portion of the grid. The grid also provided some visual decision aiding to reinforce the haptic aiding. When a block was rotated so its top surface matched a part of the design that had not yet been assembled in the grid, one or more squares (as applicable) changed color to green to recommend placement of the active block (also see Figure 3 (b)). An additional block image was presented in the upper right portion of the display (see Figure 3 (b)). If a

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participant attempted to place a block in the wrong part of the grid, the image showed the correct orientation for the top of the block. Due to these features, in particular the rejection of incorrect orientations, it was impossible for participants to make errors in the completed designs. The only failed designs occurred when participants could not complete a pattern within the 3-minute time limit.

Insert Figure 3 about here

Variables

Independent variables included the three different types of training: (1) the Native BD training task condition, serving as a control; (2) the Basic VR condition; and (3) the Augmented VR condition with enhanced haptic control and visual aiding. Dependent variables included: (1) WAIS BD test improvement; (2) ROCF test improvement; (3) the BD training task completion time; and (4) learning percentage calculated based on BD training task completion time. Percent

improvement data for (1) and (2) were also calculated using baseline and post-training test scores in the following formula:

Percent improvement = (Post-test Score – Baseline test Score) / Baseline test Score x 100

The BD training performance was collected in order to allow for assessment of the impact of the VR-haptic interface on task/training performance. Subjective confidence ratings of ROCF test accuracy were also collected during the first and final sessions of the experiment. More details on the response measures are provided below in the results section.

Hypotheses

In general, we hypothesized that participant test scores (ROCF, BD) would improve as a result of completing any of the three training conditions with their non-dominant hand (Hypothesis (H)1). Basic VR training was not expected to exceed traditional physical task training in improving participant motor skills due to the fact that no additional perceptuo-motor aiding was provided as part of the VR simulation (H2). The Augmented VR condition was expected to lead to improved performance over the Native form of the BD training task due to the visual and haptic enhancements of the VR simulation beyond the constraints of the traditional training (H3). The visual enhancements, including the design grid highlighting and correct block orientation image were expected to assist participants with Steps 1-3 in Hoffman et al. (2003) list for BD training completion and the resistive and attractive haptic forces were expected to aid in Steps 4-5.

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RESULTS

The primary aim of the study was to identify differences between baseline psychomotor and post-test scores occurring as a result of the various forms of training. The ROCF and BD test scores violated normal distribution assumptions; therefore, nonparametric analyses were conducted on the improvement in BD and ROCF test scores from baseline to post-test. Studentized t-tests were also used for orthogonal contrasts among the training conditions in terms of baseline test scores to identify differences in groups prior to training. Bonferroni correction was applied to account for potential inflation of the Type I error based on the number of tests. As secondary analyses, a series of repeated measures ANOVAs were conducted to investigate the effects of the test conditions during training. In addition, an analysis of task learning rates under the various conditions was conducted using a general linear model for longitudinal data analysis. The results of the various analyses are presented in the following sections.

Baseline and Post-testing

A one-way ANOVA test was performed on the BD baseline test data showed no significant differences among the training conditions, verifying that no participant group had an advantage over another prior to training. The means and standard errors summarizing differences between BD test baseline and post-test scores are presented in Table 3.

Insert Table 3 about here

A comparison of baseline and post-BD scores for each condition using one-tailed Wilcoxon signed-rank paired tests revealed highly significant improvements in scores as a result of training for all three conditions (Augmented VR: $p=0.007$; Basic VR: $p=0.007$; Native: $p=0.007$). However, an ANOVA comparing the BD test scores did not reveal any significant differences attributable to the training condition. Figure 4 present the difference between pre- and post-BD score across three conditions.

Insert Figure 4 about here

Results of an initial one-way ANOVA comparing the ROCF baseline and post-scores across the three conditions were also insignificant; that is, the native and VR forms of training showed comparable effects in terms of changes in ROCF scores. However, a review of the ROCF performance and experimenter observations made during testing revealed that one participant completed the post-test more than twice as fast as the group mean (greater than the mean plus two standard deviations), and drawing performance suffered as a result. ROCF instructions identify drawing scale and accuracy as performance criteria and emphasize the need for care in reproduction of the figure. According to experimenter logs, the specific subject did not draw the picture with care but attempted to create a rough figure as fast as possible. Related to this, the subject's post-test score (20) was substantially lower than the pre-test score (27). It was therefore determined that the participant did not follow experiment instructions at the end of the session. An observation made on another participant during testing indicated variable fatigue in the use of the haptic device that resulted in substantially reduced performance. Although ROCF scores are generally inversely related to performance time, this participant produced the ROCF task completion times during post-testing greater than the mean time plus two standard deviations yet the participant's ROCF score did not improve as a result of the additional time spent performing the task. An experimenter also recorded in a log book that the subjects appeared to be sleep deprived and unable to concentrate on the reproduction of the complex figure. For these reasons, the test data for these two participants was not considered representative of the sample population. Consequently, outlying response observations were excluded from further statistical analyses and replaced with the condition mean.

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The results of ROCF pre- and post-testing appear in Table 4. The left side of the table includes the ROCF test scores, which can range from 0 to 36. P-values related to the scores identify significant differences between pre- and post-test scores based on one-tailed Wilcoxon signed-rank paired tests. The right side of the table lists ROCF test completion times recorded during pre- and post-testing. Although speed is not a traditional ROCF performance measure, analysis of the results revealed an inverse relationship between ROCF scores and completion times and was included in subsequent analyses. As with the ROCF scores, the p-values identify significant differences between pre- and post-test completion times based on one-tailed Wilcoxon signed-rank paired tests.

Insert Table 4 about here

Comparisons between baseline and post-ROCF scores and times were conducted for each condition using one-tailed Wilcoxon signed-rank paired tests. Only Augmented VR participants showed a significant improvement in scores as a result of training (p=0.021) as well as a significant improvement in test times as a result of training (p=0.039). These findings supported our hypothesis (H3). On this basis, additional one-tailed Wilcoxon paired tests were conducted to

compare Augmented VR baseline and post-scores for individual ROCF units (see Figure 1(a) for ROCF unit identifiers). Results revealed a significant improvement in scores for Unit 6 (p=0.036) (a rectangle in the left side of the figure) and Unit 9 (p=0.036) (a triangle in the top-center of the figure). In addition, all participants showed limited improvement in drawing Unit 12 (five parallel short lines) and performed nearly perfectly on other units (2-5, 10 and 16). Figure 5 shows a comparison of ROCF pre- and post- scores (Figure 5 (a)) and times (Figure 5 (b)), along with standard errors across the three conditions.

Insert Figure 5 about here

An additional analysis of the percent improvement between ROCF pre- and post-test scores was performed using a Kruskal-Wallis nonparametric test. Results revealed significant differences among conditions in terms of the percent improvement in test scores. (chi-square = 7.732, p= 0.021). Post-hoc analyses using Bonferroni correction on the training condition test score data revealed a significant difference (p=0.011) between Augmented VR training and the Native BD

task. This finding was in line with the hypothesis and provides support for the Augmented VR condition for psychomotor skill learning as compared to the Native task.

Training

Additional analyses were performed on the BD task training data to further interpret the performance differences among the conditions revealed by the differences in test scores. Each BD score (traditionally used to evaluate task performance) is a combination of completion time and accuracy, summarizing performance on each design with a composite score between 0 and 7. Because BD scoring was designed for the Native task and does not account for aspects of the VR design that affect performance (e.g., interacting with the blocks through a stylus instead of directly handling them), traditional scoring was not used to evaluate training performance. The task completion time part of the score, which was limited to 3 minutes, was used instead.

Results of a repeated measures ANOVA on BD training task completion time showed a significant main effect of condition ($F(2, 21)=18.72$, $p<0.0001$) across trials. Post-hoc analysis revealed significantly lower BD training task times for the Native task training group as compared with the VR training groups. This finding was to be expected in that the haptic interface as part of the VR simulation imposed some limitations on hand motion as compared to normal motion behavior in the real-world task. However, the BD training task times associated with the two VR groups were comparable (see Figure 6).

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Insert Figure 6 about here

With respect to task learning during training, we initially applied learning curve analysis (according to Konz and Johnson (2004)) to the BD task time response in order to estimate learning rates for each training group. Power functions ($y_n = y_i * x^b$) were fit to the training data and goodness of fit was assessed using sample coefficients of determination (r^2 values). Among participants, model fit levels ranged from $r^2 = 0.46$ to 0.95. Estimation of task learning rates ($k = 2^b$) from the model power coefficients revealed rates to be relatively similar among the test conditions (~79%). Because of the low r^2 values from the power functions, we applied a general linear model (GLM) for longitudinal data analysis to the BD task time response instead of the learning curve analysis. Such models are useful for describing changes in the mean response for an experimental group over time (Davidan, 2008). The general form of the model is: $y_{ij} = \beta_0 + \beta_1 * t_i + \varepsilon_{ij}$, where y_{ij} represents the BD training task completion time for the ith participant (i = 1,2,3…24) in the jth trial (j = 1,2,3…8). β_0 represents the function intercept for the specific training group (i.e., Native task, Basic or Augmented VR) and β_1 represents the slope of the learning curve for the group at the jth trial. It is also important to note that these models assume an autoregressive covariance structure over time; that is, performance observations are assumed

to be correlated but the correlation decreases with time as participant performance becomes more stable. The slopes and intercepts for the GLMs on the longitudinal data for each training condition are presented in Table 5. In general, the level of model fit to the data was substantially greater than for the power function analysis.

Insert Table 5 about here

Contrast results revealed that Basic and Augmented VR groups achieved significantly greater reductions in task time across trials than the Native task group (see Table 6). However, intercepts and slopes between the two VR groups were not significantly different from each other (see Table 6). This indicated that although participants in the VR training groups performed worse in terms of task completion time as compared with those in the Native training group, they showed a significantly faster learning rate for the specific task interface conditions.

Insert Table 6 about here

DISCUSSION

With respect to the hypotheses that all participant test scores would increase as a result of training (H1), only the Augmented VR condition resulted in a significant improvement in ROCF performance. (We offer some explanation of this finding below.) Participant BD test performance showed no significant improvements for any of the three training conditions. This might be due to significant differences in performance between individuals within training groups and among groups. However, results did support the third hypothesis (H3) and suggested that the Augmented VR condition supported greater ROCF improvements as compared to the Native task and Basic VR conditions. Therefore, there is evidence that Augmented VR with haptic and visual aids may facilitate greater improvements in psychomotor skills over the Native BD and Basic VR conditions. Finally, the Basic VR training results also supported the second hypothesis (H2) as there was no significant improvement over the Native BD task. However, this may be due, in part, to the limited sample size for the study.

It is important to note that the Basic and Augmented VR training conditions used the same control device as the ROCF task (i.e., the Omni) and required the same grip. This means that

participants in the VR conditions received 3 hours of additional training with the stylus than participants performing the Native task. It is therefore reasonable to assume that the VR participants would have some advantage over the Native task participants when performing the ROCF post-test. However, the more important finding of this study is the advantage of the Augmented VR over the Basic VR in terms of performance and task learning rates. Results clearly demonstrated the advantages of the visual (design grid highlighting and correct block orientation image) and haptic (resistive and attractive forces) aiding as part of the Augmented VR simulation and provide a proof of concept of the augmented design for supporting motor skill training and possibly rehabilitation. The presence of augmented aids during BD training appeared important to the subsequent ROCF test figure reproduction. One possible explanation for the difference is that the visual and haptic cues in the augmented scenario served to train subjects in mentally segmenting design patterns, which was relevant to drawing unit identification in the ROCF test.

With respect to the BD task completion times during the training sessions, the Native task produced shorter times, overall, than the Basic and Augmented VR conditions. This was partly due to the use of the stylus in the VR conditions instead of grasping blocks directly by hand; a known limitation of the haptic interface design (MacLean, 2008). Evidence of this performance gap can be seen in Figure 6, which shows a substantial difference in completion times for the first trial. Despite the haptic device training, the novel nature of the technology to participants required some additional learning to effectively manipulate blocks in the virtual environment. However, the learning rates in the VR conditions indicate that participants adapted quickly to the haptic device. Furthermore, learning rates and performance times (other than in the initial

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training trial) for the Basic and Augmented VR conditions were similar, despite the Augmented VR having additional haptic and visual features required for task performance. This suggests that the design of additional augmented features facilitated significant improvements in post-test performance without sacrificing training task performance, as compared to the basic VR environment.

Results revealed Augmented VR task completion times were longer and error rates were artificially low compared to the Native task. These results were somewhat expected as the augmented visual features drew participant attention from direct task performance and the haptic features prevented any participant errors in the simulation. It is important to recall here that training performance was evaluated based on task completion time instead of traditional BD task scoring, which combines speed and accuracy. It is possible that modifications to the augmented visual and haptic features may reduce user perceptual loading as well as control for errors, allowing for Augmented VR task times to more closely approximate Native task performance along with additional task errors. Improving the haptic VR features to reduce the gap between Native and VR task performance times and error rates and incorporating traditional scoring methods is an objective for the ongoing research.

Although this research draws parallels between physical and cognitive characteristics of non-dominant performance and motor planning and control implications of mTBI, there remains a need to test an actual pathological population using the VR technology. A follow-on investigation has been planned to involve current mTBI patients at the Durham Veteran's

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Administration Medical Center to assess the effectiveness or enhanced VR motor training simulation designs for addressing motor planning and control disabilities.

CONCLUSIONS

This study demonstrated the utility of augmented VR-based haptic simulations for training motor skills to address physical and cognitive limitations. This was an initial investigation of non-dominant manual performance by healthy participants to provide insight for the design of VR simulations to support rehabilitation of motor skills in mTBI patients. The study also identified unique visual and haptic features of VR simulation design (facilitating visual pattern recognition and object manipulation and placement) that appear to support efficient and effective motor skill development.

Regarding the design features of the prototype VR and haptic simulations, there were three key motor and visual-spatial processing issues observed during the experiment that need to be addressed to potentially improve the performance of the simulation tool. First, with respect to motor task performance, some participants experienced difficulty in rotating virtual blocks using the stylus of the haptic device. This was due to kinematic limits of wrist rotation while holding the stylus with a precision grip. Second, with respect to visual-spatial processing, field-dependent participants might have found it difficult to determine how a design was constructed due to limited ability to distinguish each block in a pattern and to identify correct block positions and orientations (Witken et al., 1977). Third, observing individual block orientations to achieve a desired pattern imposed an extra challenge for the participants. In the Native task, participants could change their perspective by moving their head or using well-practiced finger motions to

observe various sides of a block. In the VR simulations, a participant's perspective of the task environment was static, and block rotation was translated through the stylus instead of occurring directly. In the VR, when the side of a block that matched the model was not in view, it was more challenging for participants to orient the block correctly.

In general, the additional effects of the augmented visual cues on user cognition are a concern for the ongoing research. While the augmented VR condition provided some advantage over the basic VR, the visual aiding introduces features that may increase task complexity for some populations. These issues are to be addressed in future studies as part of the program of research.

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ACCEPTED MANUSCRIPT

List of tables

Table 1. Overview of experimental sessions

Table 2. Materials and apparatus used for the three experiment conditions. Native refers to the standardized WASI materials used to administer the task in a clinical setting.

Table 3. WAIS BD pre (baseline) and post-test scores for each condition, with standard errors. P-values identify significant differences between baseline and post-test scores based on Wilcoxon signed-rank paired tests.

Table 4. ROCF pre (baseline) and post-test scores and completion times for each condition, with standard errors. P-values identify significant differences between baseline and post-test scores and times based on Wilcoxon signed-rank paired tests.

Table 5. Estimates for intercepts and slopes from general linear fit (based on training task completion time (seconds))

Table 6. Contrast results identifying significant results of the general linear fit (based on training task completion time)

Table 1. Overview of experimental sessions

Day	Task	Purpose	Interface	# Trials
Day 1	ROCF	Test	Custom workstation with PHANTOM Omni	1
	WAIS-III Block Design	Test	Standard test materials	1
	WASI Block Design	Training	By condition	2
Day 2	WASI Block Design	Training	By condition	3
Day 3	WASI Block Design	Training	By condition	3
Day 4	ROCF	Test	Custom workstation with PHANTOM Omni	1
	WAIS-III Block Design	Test	Standard test materials	1

ACCEPTED MANUSCRIPT

Table 2. Materials and apparatus used for the three experiment conditions. Native refers to the standardized WASI materials used to administer the task in a clinical setting.

Condition	Platform	Participants
Native	Native WASI BD Task	8
Basic	WASI BD VR Task	8
Augmented	WASI BD VR Task	8

Table 3. WAIS BD pre (baseline) and post-test scores for each condition, with standard errors. P-values identify significant differences between baseline and post-test scores based on Wilcoxon signed-rank paired tests.

	N	BD Pre Test	BD Post Test	p-value
Augmented	8	46.63 (3.21)	55.88 (2.26)	0.007*
Basic	8	48.50 (2.95)	56.38 (2.80)	0.007*
Native	8	47.25 (1.83)	58.25 (2.23)	0.007*

* Significant at the p<0.05 level

ACCEPTED MANUSCRIPT

Table 4. ROCF pre (baseline) and post-test scores and completion times for each condition, with standard errors. P-values identify significant differences between baseline and post-test scores and times based on Wilcoxon signed-rank paired tests.

		ROCF Score			ROCF Completion Time		
Condition	N	Pre Test	Post Test	p-value	Pre Test	Post Test	p-value
Augmented	7	26.93 (1.49)	29.71 (0.92)	0.021*	457.35 (69.12)	397.51 (54.89)	0.039*
Basic	8	26.56 (1.13)	28.63 (1.57)	0.102	416.11 (44.20)	393.93 (40.06)	0.231
Native	7	28.57 (0.91)	26.71 (1.53)	0.876	407.92 (51.56)	404.54 (84.25)	0.298

* Significant at the p<0.05 level

Table 5. Estimates for intercepts and slopes from general linear fit (based on training task completion time (seconds))

Contrast	Conditions	Completion Time Estimate (standard error)
Intercept	Augmented VR	752.50 (38.74)
	Basic VR	947.50 (84.77)
	Native	365.99 (33.59)
Slope	Augmented VR	-52.19 (7.07)
	Basic VR	-65.27 (11.54)
	Native	-25.47 (4.49)

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Table 6. Contrast results identifying significant results of the general linear fit (based on training task completion time)

Contrast	Conditions	F-value	p-value
Intercept	Augmented vs. Basic	F (1,21) = 4.38	0.048
	Augmented vs. Native	F (1,21) =56.80	< 0.0001*
	Native vs. Basic	F (1,21) =40.67	< 0.0001*
Slope	Augmented vs. Basic	F (1,165) =0.93	0.3354
	Augmented vs. Native	F (1,165) =10.16	0.0017*
	Native vs. Basic	F (1,165) =10.33	0.0016*

* Significant at the p<0.0167 level, using Bonferroni correction

ACCEPTED MANUSCRIPT

List of Figures

Figure 1. ROCF and Block Design test materials.

Figure 2. ROCF test and BD training apparatus.

Figure 3. VR BD simulation conditions during training.

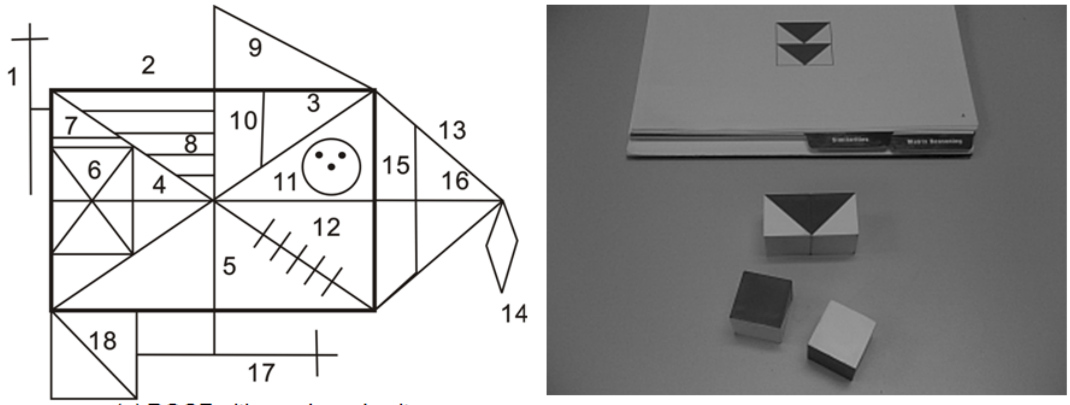
Figure 4. Significant increases between pre- and post-test Block Design scores (with standard errors) for the three experiment conditions

Figure 5. Changes in ROCF performance indicated by pre- and post-test scores (with standard errors). (a) shows average improvement and decline in ROCF scores, with augmented VR (*) showing significant improvement. (b) shows average reductions in ROCF completion times (s), again with only the augmented VR (*) showing significant improvement.

Figure 6. Plot of reductions in average Block Design training task performance times across conditions (with standard errors) for each trial. Participants were able to complete the task faster in the Native condition compared to the two VR conditions. VR participants showed greater improvements over time, but were not able to perform at Native condition levels.

ACCEPTED MANUSCRIPT

Figure 1. ROCF and Block Design test materials



(a) ROCF with numbered units

(b) Block design model and blocks

Figure 2. ROCF test and BD training apparatus

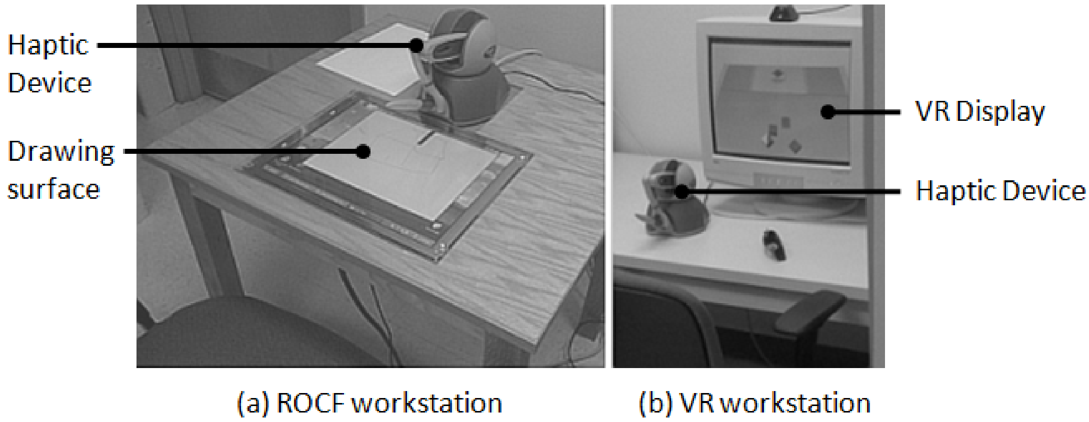


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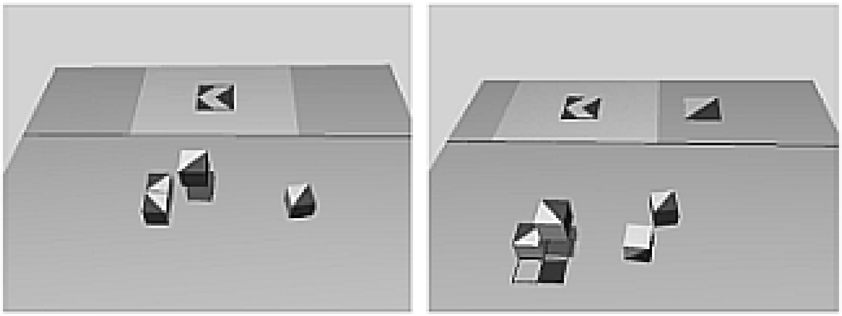
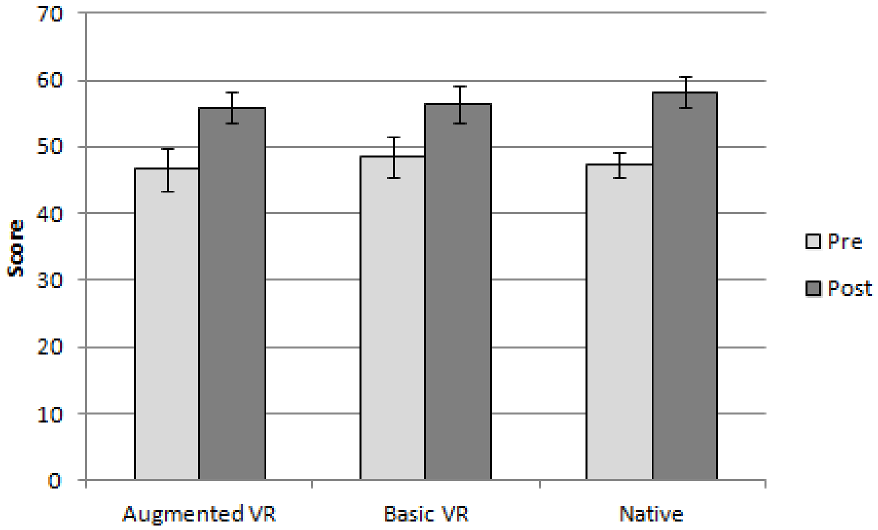
Figure 3. VR BD simulation conditions during training



(a) Basic VR condition (b) Augmented VR condition

ACCEPTED MANUSCRIPT

Figure 4. Significant increases between pre- and post-test Block Design scores (with standard errors) for the three experiment conditions



ACCEPTED MANUSCRIPT

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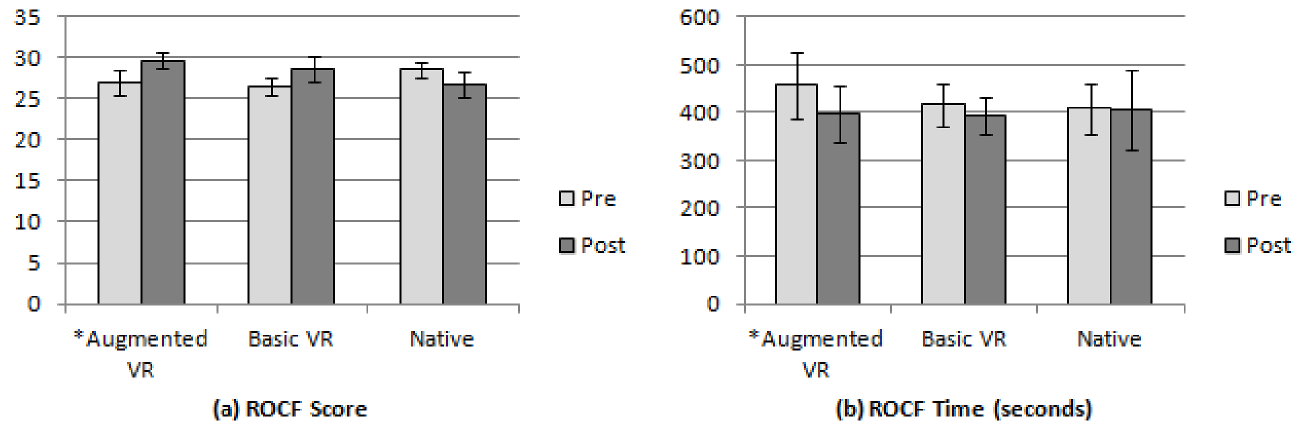

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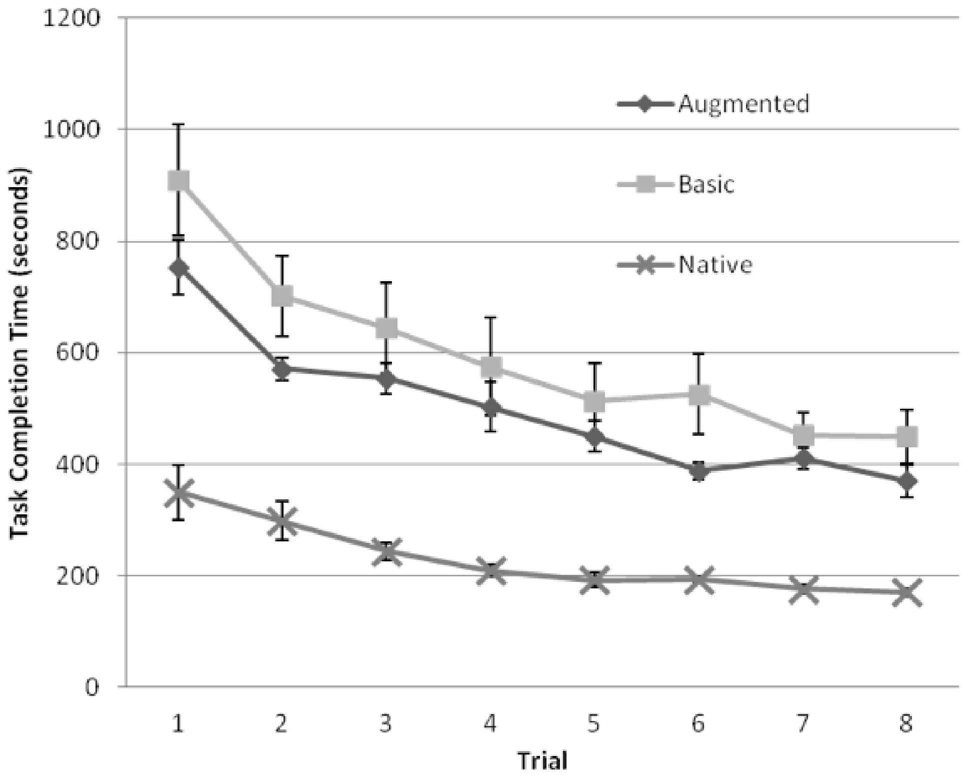

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