Comparison of Enhanced Visual and Haptic Features in a Virtual Reality-Based Haptic Simulation

Michael Clamann, Wenqi Ma, and David B. Kaber

Edwards P. Fitts Department of Industrial and Systems Engineering,
North Carolina State University, Raleigh, NC, USA
`{mpclaman,wma4,dbkaber}@ncsu.edu`

Abstract. An experiment was conducted to compare the learning effects following motor skill training using three types of virtual reality simulations. Training and testing were presented using virtual reality (VR) and standardized forms of existing psychomotor tests, respectively. The VR training simulations included haptic, visual and a combination of haptic and visual assistance designed to accelerate training. A comparison of performance test results prior to and following training revealed conditions providing haptic assistance to yield lower scores related to fine motor skill training than the visual-only aiding condition. Similarly, training in the visual condition resulted in comparatively lower cognitive skill scores. The present investigation incorporating healthy subjects was designed as part of an ongoing research effort to provide insight on the design of VR simulations for rehabilitation of motor skills in patients with a history of mTBI.

Keywords: haptics, virtual reality, rehabilitation.

1 Introduction

In this research, we compared the effects of visual and haptic assistance for motor training using a virtual reality (VR)-based haptic simulation. Previous research on VR-based haptic simulation has demonstrated the efficacy of such tools for occupational therapy, including motor function rehabilitation [1-4]. The advantages for motor training include reducing trainer workload and training task costs by delivering any number of therapy sessions while maintaining accuracy and objectivity. Virtual reality can also enhance training by incorporating augmented controls and decision features during therapy sessions to aid user performance. Such features include precise corrective haptic control forces and enhanced visual aids that respond automatically to user actions. Similar enhancements would be difficult to implement in a physical system. However, questions remain on how to best implement these technologies and what specific VR design features might serve to accelerate motor learning beyond VR training tasks that merely replicate traditional training environments.

Previous research by our team identified combinations of augmented visual and haptic features that may provide therapeutic benefits over traditional VR systems [5]. The experiment design replicated a simplified occupational therapy regimen in which

M. Kurosu (Ed.): Human-Computer Interaction, Part IV, HCII 2013, LNCS 8007, pp. 551–560, 2013.

a drawing and pattern assembly task represented occupational tasks that were anticipated to improve as a result of therapy. A VR reproduction of the block design (BD) subtest from the Wechsler Abbreviated Scale for Intelligence (WASI; [6]) was developed to be used to train subject motor skills in a course of simulated therapy. The BD subtest requires subjects to build replicas of patterns using blocks printed with simple patterns. Subjects are given a collection of nine red and white cubes with varying patterns on each side and are asked to replicate designs shown on a series of test cards. Scoring is based on speed and accuracy. In our study, healthy subjects were trained in the BD task using the non-dominant hand to simulate minor motor impairment. Training effects were measured by comparing drawing and pattern assembly task test scores obtained before (pre-test) and after (post-test) multiple BD training sessions. Subjects were assigned to one of three groups, including performance of the native BD task using standardized test materials (i.e., test cards and nine 1-inch cubes), use of a basic VR simulation of the task, or an augmented VR simulation with additional visual and haptic aiding. Results revealed a significant improvement in post-test performance over pre-test for the augmented VR training. In general, the study supported integrating haptic control in VR for psychomotor skill training. It also provided useful information for future haptic VR simulation design. However, because visual and haptic features were combined in the augmented condition, further investigation was needed to determine the extent to which these two forms of assistance contributed individually to psychomotor training.

Prior research comparing visual and haptic training modalities has produced mixed results. In one study [7], subjects were trained to replicate a 3-dimensional (D) trajectory using a haptic controller with 3 degrees of freedom (DOF). Subjects were initially required to trace the trajectory using visual, haptic, or a combination of visual and haptic conditions. Results showed that the haptic training alone was more effective with respect to timing as compared to visual training, but less effective with respect to absolute position and shape accuracy measures. Furthermore, the researchers also found that combining visual and haptic control during training did not provide additional learning beyond that of the visual-only condition.

Another research group [8] compared the effects of training visuomotor skills using combinations of haptic guidance and visual demonstration. Their methods were similar to those used in [7], but featured a simpler trajectory, additional training and additional test trials to more closely resemble an occupational therapy regimen. The researchers found that both visual-only and the combination of visual and haptic training allowed subjects to improve their ability to reproduce a novel trajectory. The results also showed that the combination of haptic and visual input did not significantly improve learning compared to the visual input alone, which supported the findings of [7]. Moreover, the researchers found that subjects receiving visual training performed marginally better than those receiving a combination of visual and haptic training. The authors speculated this occurred because visual feedback is more accurate than haptic; therefore, haptic feedback does not contribute to improved performance when both types of feedback are available at the same time.

These studies suggest that assistance that combines visual and haptic components may not be more effective than visual or haptic assistance alone. However, there are several differences between the procedures used in [7] and [7] and the present study. First, the task itself is quite different (i.e., tracking vs. pattern assembly). Second, in the prior studies the training and test tasks were the same. In the present study, in contrast, we implemented a training task designed to affect performance in a different test task, representing an occupation-related activity distinct from the training task.

The present study used the apparatus incorporated in the prior work, including a VR version of the Rey-Osterreith Complex Figure (ROCF; [9]) test to represent the occupational task and a VR-based haptic simulation of the BD (VR-BD) subtask from the WASI [6], representing a training task [10], [5].

The VR BD training task used a combination of haptic and visual aiding. Haptic assistance in the VR-BD included scheduled snap forces and rejection forces. The snap force was expected to assist users by prompting the correct movement when approaching a target block position at close range [11]. It was designed to reinforce correct placement and reduce the need for additional visual verification of block position. The rejection force, in contrast, was designed to reveal block placement errors. Both forms of haptic assistance were designed to assist users passively (i.e., without additional voluntary control of the haptic device).

Visual assistance providing passive positive feedback during correct block placement and corrective feedback during incorrect placements was also implemented. Subjects could also actively request assistance to "decompose" a design to reveal in individual block positions and orientations within a design. Use of this feature came at the cost of additional task time while activating the assistance. Precise details on the nature of the haptic and visual aiding are provided in the methods section
below.

The current study investigated the influence of these augmented visual and haptic VR features, independently and in combination, on subjects learning. Based on the previous research, three different augmented VR conditions (i.e., haptic, visual or combined haptic and visual aiding) [12] were delivered to healthy subjects through a simplified occupational therapy regimen. This study also served as an additional step in the development of a proof of concept of the VR system to be used with patients with a history of minor traumatic brain injury (mTBI) for motor skill rehabilitation.

2 Methods

Twenty-four subjects between the ages of 18 and 44 were recruited for the study. All subjects were required to have 20/20 or corrected to normal vision and to exhibit right-hand dominance. Right-hand dominance was confirmed using the Edinburgh Handedness Inventory [13]. Subjects were required to complete all testing and training as part of the experiment using the left hand. This requirement was used to simulate minor motor impairment and to disadvantage subject task performance in order to promote sensitivity to the training conditions.

The VR-BD task was presented on a PC integrated with a stereoscopic display using a NVIDIA® 3D Vision™ Kit, including 3D goggles and an emitter (see Figure 1). A SensAble Technologies PHANTOM Omni® Haptic Device was used as the haptic control interface. The Omni includes a boom-mounted stylus that supports 6 DOF movement and 3 DOF force feedback. The interface recorded subject performance data automatically.

Fig. 1. VR-BD training apparatus including PHANTOM Omni and NVIDIA 3D Vision kit

Experiment sessions were designed to simulate occupational therapy sessions. Two tests, the ROCF and BD subtest from the Wechsler Adult Intelligence Scale – Third Edition (WAIS-III; [14]), represented occupational tasks anticipated to improve as a result of therapy. These two tests were administered once prior to training to evaluate baseline psychomotor performance and again following multiple psychomotor training sessions in order to measure performance improvements. The training task was an updated version of the VR-BD task used in previous studies [5], [12].

The ROCF was administered using a VR adaptation of the task [10]. The task interface was designed to replicate a drawing setup. It included a custom workstation featuring a flat-screen monitor mounted in a tabletop and another Phantom Omni haptic device (see Figure 2, left). To perform the ROCF, subjects used the Omni to virtually draw the complex figure elements directly on the horizontally-aligned monitor (see Figure 2, right, for the ROCF image with numbered units). Rey Osterreith 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 simulation recorded subject test performance data and calculated the scores automatically.

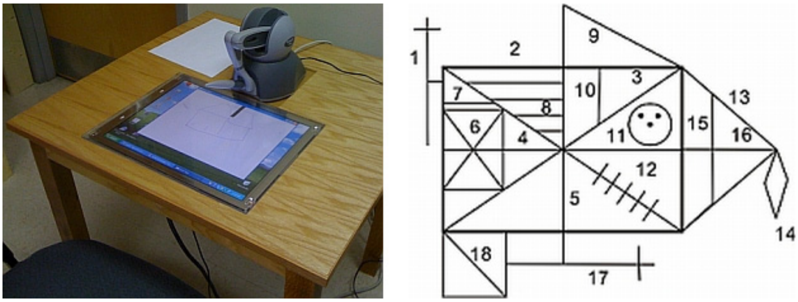


Fig. 2. ROCF workstation and test image

In addition to the ROCF test, subjects completed the WAIS BD subtest during pre- and post-testing to further characterize training effects. The WAIS BD task used for testing and the WASI BD task used for training are identical except for the patterns completed by the subjects. During testing, the WAIS BD was administered using standardized materials.

The features of the VR-BD training task included a virtual tabletop divided into two parts, including a display area (see Figure 3 (a)) and a work area (see Figure 3 (b)). The display area presented the pattern (see Figure 3 (c)) to be replicated by a subject. The work area was used for arranging the blocks. Like the standardized version of the BD task [6], virtual red and white blocks printed with either solid or cross-sectional patterns on each side were distributed randomly in the work area. The design was presented in the display area, and subjects manipulated the blocks to reproduce the picture as quickly as possible. All patterns were constructed with the aid of a target grid (see Figure 3 (d)), which appeared as a 2x2 or 3x3 collection of squares in the work area, depending on the dimensions of the pattern.

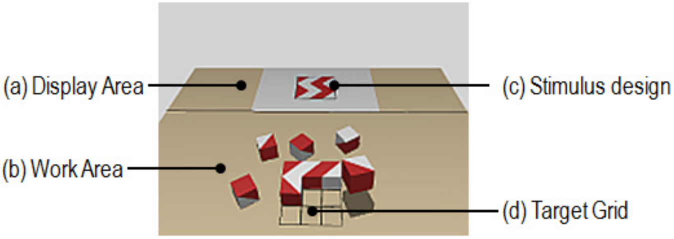


Fig. 3. VR-BD training display layout

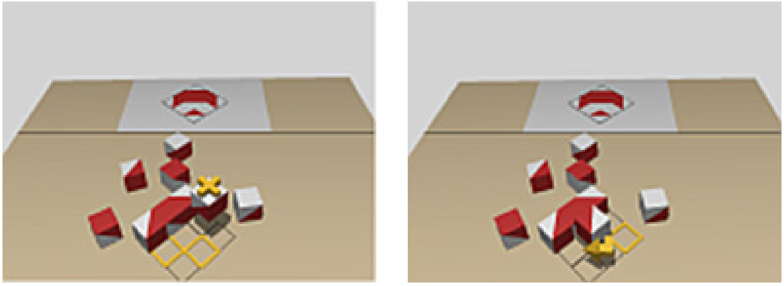
The Phantom Omni was used to manipulate a cursor appearing on the display during training. Blocks could be grasped by touching the cursor against them and pressing and releasing the button on the stylus of the haptic device. A block could then be lifted from the table surface and rotated along any axis using the stylus (without holding the button). A block was released upon return to the table surface. Haptic features representing physical properties of the blocks and the table were also included.

The type of aiding represented the independent variable, including the (1) haptic, (2) visual, or (3) combination conditions. The dependent variables included: (1) ROCF test performance and (2) WAIS BD test performance.

2.1 Procedures

There were three main parts of the experiment for data collection: (1) an evaluation of pre-test performance, (2) multiple training sessions, and (3) the post-test to measure improvement. The three parts of the experiment were distributed across four days, with testing scheduled on the first and last days and training taking place on Days 1-3. Each subject completed eight VR-BD trials in total (10 designs per trial, as required by the established WASI protocol). The combined duration of the three training visits was approximately 3 hours, which was established through pilot testing and prior work [5].

The experiment followed a between-subjects design and each subject was assigned to one aiding type (haptic, visual, or combination) for VR-BD training with a total of eight subjects per condition. The combination condition incorporated all the haptic and visual features. Haptic aiding included snap forces that pulled blocks to a target position during correct placement and rejection forces that acted against the block during incorrect placement. Visual aiding provided feedback during incorrect block placements. If a user attempted to place a block in an incorrect orientation in the target grid, a yellow “X” or an arrow would be superimposed on the block. The “X” would appear when the wrong block face was showing (see Figure 4 (a)). The arrow would appear when the correct block face was showing, but it was rotated incorrectly (see Figure 4 (b)). The arrow indicated the direction in which the block needed to be rotated for correct orientation in the target grid square. If a user moved a block in the correct orientation over the grid, those squares in the grid at which the block could be placed without error were highlighted in yellow.


(a) "X" indicating the wrong block face

(b) "Arrow" recommending a rotation

Fig. 3. VR-BD visual assistance during block placement

In addition to the passive visual assistance, subjects could request additional assistance during training. Touching the cursor to the pattern at the top of the screen or the target grid caused visual cues to be displayed on how to correctly place blocks. Specifically, the cues indicated the orientation and locations of individual block faces. Touching the cursor to a target grid square highlighted the corresponding square in the stimulus pattern and any blocks in the workspace that matched the selected square. Likewise, touching the stimulus pattern would highlight the corresponding square on the target grid. The gridlines disappeared when any surface outside of the stimulus pattern and grid was contacted with the cursor.

2.2 Hypotheses

We hypothesized that all three VR conditions would result in ROCF and WAIS BD test performance improvements (Hypothesis (H)1). Based on the results of previous study [5], it was also expected that training in the combination condition would result in greater improvements in ROCF performance as compared to visual or haptic aiding, alone (H2). This is also consistent with existing notions that suggest receiving feedback via multiple compatible sensory modalities can produce better performance than from a single modality [15].

3 Results

Subject pre-test performance was compared across conditions using Kruskal-Wallis tests. No significant differences attributable to the training condition were revealed. In other words, subjects began data collection at similar performance levels. Pre-and post-test data were analyzed to identify differences in training effects among the three conditions. The results of ROCF and WAIS BD pre- and post-test scores are presented in Table 1.

Table 1. Results of ROCF and WAIS-BD test scores

		ROCF			**WAIS-BD**		
Condition	N	Pre	Post	%	Pre	Post	%
Comb.	8	25.75	28.25	13.84	44.50	53.00	23.56
Haptic	8	27.00	28.13	7.63	42.50	55.63	31.55
Visual	8	24.63	28.19	18.50	46.38	52.63	16.61

Pre- and post-test scores were compared for each training condition. As a result of some of the response data violating the normality assumption of parametric tests, Wilcoxon rank sum paired tests were conducted to compare the various training conditions. Subject WAIS BD test scores significantly improved as a result of the visual ($p=0.018$), haptic ($p=0.007$) and combination ($p=0.004$) conditions. However, ROCF test performance did not reveal significant improvements between pre- and post-training (due to a high degree of variability in performance among subjects). Only subjects assigned to the visual condition showed marginally significant improvements in ROCF scores (p=0.061). Additional analyses on the percent change in WAIS BD test scores revealed no significant differences in the extent of improvement among training conditions. Statistically speaking, the three conditions resulted in similar increases; however, on average, the haptic condition showed the highest percentage of WAIS BD test improvement.

4 Discussion

The results of the experiment revealed that training in any of the three conditions increased WAIS BD test performance, which was consistent with H1. However, contrary to H1, training did not necessarily lead to increases in ROCF (surrogate occupational task) performance. Beyond this broader result, the degree of improvement in test task performance may vary by condition. There are several possible reasons for this. The snap force feature implemented as part of the haptic aiding condition pulled blocks to their final position as they were moved near the design construction. In effect, while the subject was responsible for gross movement, the honing portion of the task (requiring placement of the block at the target location) was offloaded to the system, and subjects were not required to perform any fine positioning on their own. This means that conditions providing haptic assistance (i.e., the haptic and combination conditions) provided less fine motor skill training than the visual-only aiding condition, which required fine movements during final block positioning. These fine motor skills may have been useful when replicating the ROCF using the haptic device. This may explain the marginally significant increase in ROCF scores under the visual aiding condition (where fine motor movement was not automated) as well as the lack of benefit in terms of ROCF scores as a result of haptic aiding.

Similar results were observed in WAIS BD test performance following training in the visual condition. The visual aiding was designed to assist subjects in parsing the stimulus designs into individual squares corresponding to block faces. This offloaded cognitive aspects of the task to the system; that is, subjects were not required to perform mental segmentation of a block design. There is evidence that subjects receiving visual assistance relied on the automated assistance rather than honing their own cognitive strategies [16]. The additional visual and mental processing of a stimulus pattern required of subjects assigned to the haptic condition likely helped them refine their strategy for stimulus segmentation, as compared to the visually aided subjects. It is likely that this is the reason that haptically aided subjects showed the greatest increases in WAIS BD test performance. While subjects receiving visual assistance were able to rely on visual aids that parsed the design and recommended block orientations and increase scores, subjects receiving haptic assistance had to learn these strategies on their own.

It was expected that training in the combination condition would lead to the greatest increases in test performance due to the presentation of combined haptic and visual cues (H2). However, results did not support this expectation. In fact, the combination condition led to mediocre training effects in terms of ROCF test score improvement, as compared to the visual-only group, and WAIS BD test score improvement for the haptic-only group. This may be due to the combination of visual and haptic assistance increasing cognitive load or distracting subjects during training. This observation is also consistent with the findings of [7], which proposed that vision may interfere with haptic cues during training.

5 Conclusion

The outcomes of this work are important to VR-based motor training system design. While a form of aiding may be developed to assist psychomotor task performance during training, it may also hinder development of motor and cognitive skill requirements that are allocated to automated assistance. This raises a distinction between designing for training task performance and designing for motor skill learning. During VR-BD task training, subjects could rely on visual aiding instead of developing a strategy for parsing the blocks in the model [16]. However, by offloading some cognitive aspects of the task to the automation, these subjects received less training that could improve WAIS BD test scores where visual aiding was not available.

One limitation of the present study was the use of unimpaired subjects. Although parallels were drawn between physical and cognitive characteristics of non-dominant performance and motor planning and control implications of mTBI, there is a need to test an actual pathological population using the VR technology. For the next phase of this research, in addition to recruiting unimpaired subjects, we will recruit subjects from a pathological population to observe the effects of VR-based haptic training on patients with a history of mTBI, including fine motor skill implications. We also plan to extend the test data by incorporating functional magnetic resonance imaging (fMRI) during pre- and post-test procedures to measure changes in brain activity as a result of VR-BD training.

Acknowledgements. This research was supported by a grant from the National Science Foundation (NSF) (No. IIS-0905505) to North Carolina State University. The technical monitor was Ephraim Glinert. The views and opinions expressed on all pages and in all documents are those of the authors and do not necessarily reflect the views of the NSF.

References

1. Merians, A.S.: Virtual Reality-Augmented Rehabilitation for Patients Following Stroke. Physical Therapy 82(9), 898 (2002)
2. Wiederhold, B.K., Wiederhold, M.D.: The future of cybertherapy: improved options with advanced technologies. Studies in Health Technology and Informatics 99, 263–270 (2004)

3. Jang, S.H., You, S.H., Hallett, M., Cho, Y.W., Park, C.M., Cho, S.H., et al.: Cortical reorganization and associated functional motor recovery after virtual reality in patients with chronic stroke: an experimenter-blind preliminary study. Archives of Physical Medicine and Rehabilitation 86(11), 2218–2223 (2005)
4. Holden, M.K.: Virtual environments for motor rehabilitation: review. Cyberpsychology & Behavior 8(3), 187–211 (2005)
5. Clamann, M., Gil, G.-H., Kaber, D.B., Zhu, B., Swangnetr, M., Jeon, W., Zhang, Y., Qin, X., Ma, W., Tupler, L.A., Lee, Y.-S.: Assessment of a virtual reality-based haptic simulation for motor skill rehabilitation. In: Proceedings of the 2012 Applied Human Factors & Ergonomics Conference (CD-ROM). Taylor & Francis, CRC Press, Boca Raton, FL (2012)
6. PsychCorp: Wechsler Abbreviated Scale of Intelligence (WASI) manual. Pearson Education, Inc. (1999)
7. Feygin, D., Keehner, M., Tendick, R.: Haptic guidance: experimental evaluation of a haptic training method for a perceptual motor skill. In: Proceedings of 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS 2002), Orlando, FL, pp. 40–47 (2002)
8. Liu, J., Cramer, S.C., Reinkensmeyer, D.J.: Learning to perform a new movement with robotic assistance: comparison of haptic guidance and visual demonstration. Journal of NeuroEngineering and Rehabilitation 3(20) (2006)
9. Osterreith, P.A.: Le test de copie d'une figure complexe (The complex figure copy test). Archives de Psychologie 30, 206–356 (1944)
10. Li, Y., Kaber, D.B., Lee, Y.-S., Tupler, L.: Haptic-based virtual environment design and modeling of motor skill assessment for brain injury patients rehabilitation. Computer-Aided Design and Applications 8(2), 149–162 (2010)
11. Basdogan, C., Kiraz, A., Bukusoglu, I., Varol, A., Doğanay, S.: Haptic guidance for improved task performance in steering microparticles with optical tweezers. Optics Express 15(18), 11616–11621 (2007)
12. Jeon, W., Clamann, M., Zhu, B., Gil, G.-H., Kaber, D.B.: Usability evaluation of a virtual reality system for motor skill training. In: Proceedings of the 2012 Applied Human Factors & Ergonomics Conference, Boca Raton, FL (2012)
13. Oldfield, R.C.: The assessment and analysis of handedness: The Edinburgh inventory. Neuropsychologia 9, 97–114 (1971)
14. Wechsler, D.: WAIS-III administration and scoring manual. The Psychological Corporation, SanAntonio (1997)
15. Ernst, M., Banks, M.: Does vision always dominate haptics? In: Touch in Virtual Environments: Haptics and the Design of Interactive Systems. Prentice Hall, Upper Saddle River (2002)
16. Clamann, M., Kaber, D.B.: The Effects of Haptic and Visual Aiding on Psychomotor Task Strategy Development During Virtual Reality-Based Training. In: Proceedings of the Human Factors and Ergonomics Society annual Meeting (CD-ROM) (2012)