Comparison of Haptic Control Design for Virtual Reality-Based Assembly Task Training

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Abstract

Contemporary manual assembly tasks require fine motor skill and high-speed performance. There is a need for advanced training tools to optimize worker motor skill for such tasks. This study assessed learning effects of virtual reality (VR)-based training of motor skill with two types of haptic controls. Twenty-four participants trained in a simulation of a standardized psychomotor test (Block Design). Learning was evaluated using a physical form of the test and a LEGO® assembly task. The VR haptic controls included a stylus and a block-shaped interface resembling an element in the psychomotor test and a component in the assembly task. It was expected that the block-shaped control would more realistically represent movement constraints during the real assembly task. Comparison of test results prior to and following training revealed training with the block control to produce greater improvements in psychomotor test time and assembly task performance vs. use of the stylus control. Findings confirm that the type of control is an important component in an advanced VR-based training system for fine motor skill development. The present system could be extended for rehabilitation of motor skill in minor traumatic brain injury patients.

Keywords
Haptics, virtual reality, product assembly, psychomotor testing

1. Introduction

The use of haptics in virtual reality (VR) simulations is a growing research area with application to the domain of industrial assembly [1]. According to Xia et al. [1], VR simulations of assembly operations can be implemented for evaluating and planning assembly sequences, training operations, and determining how to allocate resources to specific operations. Previous research on the development of VR-based assembly training systems has incorporated a range of sophisticated devices, including immersive, head-mounted displays [2] for task visuals and full-body motion sensing systems [3] as control interfaces. Although fully immersive VR systems may allow for training in large-scale tasks, their cost often inhibits implementation in industrial settings [4]. Desktop systems employing conventional display screens combined with stereoscopic glasses to observe 3-dimensional images offer a low-cost alternative to fully-immersive displays. For example, Li et al. [4] developed V-REALISM, a prototype desktop system for assembly and maintenance task training. The system was designed to simulate disassembly sequences in maintenance operations, manipulating models and components for inspection, and planning disassembly sequences. Controls for V-REALISM included a keyboard and mouse combination, unlike the actual hands-on experience of industrial assembly. Such a control configuration may pose limitations with respect to transfer of training to actual disassembly task performance. Other desktop systems (e.g., [5]) have integrated more sophisticated haptic controls to better represent complex assembly tasks.

With a haptic interface, computer-controlled haptic input and output is experienced through tools called manipulandums, which can assume a variety of shapes, such as joysticks, steering wheels, thimbles and pens [6]. Modern manipulandums are physically attached to computer-controlled mechanisms, which generate haptic forces
communicated to a user. Consequently, the design of a haptic device may restrict the range of motion and size of workspace. When developing VR training systems for domains, such as driving and writing tasks, a manipulandum can be selected to match the real-world equivalent. However, when designing haptic-VR systems to simulate manual activities that are normally tool-free, like an assembly task, a manipulandum still needs to be used. In these cases, the configuration of the manipulandum may have an effect on haptic perception and user performance. With this in mind, it may be advantageous for the manipulandum to resemble task objects in order to further promote the transfer of skill training to the actual task.

Our research team previously conducted an experiment to assess learning effects of motor skill training using VR simulations of assembly tasks with a haptic device [7, 8]. The experiment design replicated a simplified occupational therapy regimen in which computer simulations of established psychomotor tests represented (target) occupational tasks, and training was provided using a VR-based simulation of the block design (BD) subtask from the Wechsler Abbreviated Scale of Intelligence (WASI; [9]; see Figure 1). The BD task requires participants to build a series of replicas of multiple block patterns of increasing difficulty. Participants are presented with a set of nine identical red and white blocks printed with either solid or cross-sectional patterns on each side. A proctor presents a stimulus card with a picture of a model design. The participant uses the blocks to replicate the picture as quickly as possible. A BD trial includes 10 to 13 stimulus designs, depending on the protocol selected. Scoring is based on speed of pattern reproduction and accuracy in placement of blocks as well as the orientation of the entire pattern.

![Figure 1. Native BD task (left) and VR-BD display (right).](image)

In our experiment, participants completed a series of psychomotor tests to establish a baseline for motor skill proficiency, followed by multiple VR-BD training sessions spread across several days. Psychomotor tests were re-administered following training for comparison with baseline assessments. The test results demonstrated utility of the VR-based haptic simulations for training psychomotor skills [7]. Beyond the positive test results, a performance gap, measured in terms of task completion time during training, was apparent between VR and native forms of the tasks. To address this performance gap, a prototype control was designed to adapt a SensAble Technologies PHANTOM Omni® Haptic Device to replicate the experience of holding a block or cube instead of the stylus control integrated with the Omni. The modification of the haptic device to include a "block-shaped" control was expected to cause training performance levels with the VR-BD task to more closely approximate (if not equal) those achieved in native BD task performance. One goal of the current work, therefore, was to determine the degree to which the design of the haptic control influenced training performance in an occupational task.

While the previous work provided insight into circumstances under which different individuals could benefit from VR-based training, a question remained as to the degree to which VR training with haptic control might benefit an occupational skill or industrial task. Therefore, the second goal of the current work was to determine how VR simulation training influences assembly skill learning. To address this goal, we expanded the experiment design from [7] to include a LEGO® assembly test task, representative of an industrial assembly operation. Hochmitz and Yuval-Gavish [10] previously used LEGO assembly to examine whether training simulators should emphasize physical or cognitive fidelity for the acquisition of procedural skills. Participants assembled a complex LEGO model under one of four experiment conditions focusing on different combinations of visual, cognitive and physical
fidelity. Post-test results were analyzed to assess procedural skill development. Results revealed that combinations of physical and cognitive training simulations could be substituted for real-world training for procedural skill acquisition.

The present work integrated the previous experiment design [7] and an adaptation of the LEGO assembly task implemented in [10]. The assembly task was administered once prior to training to evaluate baseline psychomotor performance and again following multiple VR-BD training sessions in order to measure performance improvements. It was expected that the VR training would transfer to the industrial assembly-like task resulting in post-test improvements.

2. Methods
As in our prior work, the experiment was designed to replicate an occupational therapy regimen towards improving skill in the assembly task. Therapy was represented by training in the VR-BD task. Participants performed the VR-BD simulation with one of two forms of control including: (1) the Omni haptic device with a custom block-shaped control; or (2) the Omni haptic device with the integrated stylus. Assembly task testing occurred both prior to and following VR training. Differences in assembly pre- and post-test times and errors among participants were used to identify differences in learning effects from the experiment conditions, represented by the different types of controls.

2.1 Apparatus
The VR interface for the BD task (Figure 2) was presented on a PC integrated with a stereoscopic display using a NVIDIA® 3D Vision™ Kit, including 3D goggles and an emitter. Stereoscopic rendering of the task simulation was supported by an OpenGL quad-buffered stereo, high-performance video card (NVIDIA® Quadro™). The SensAble Technologies PHANTOM Omni® Haptic Device was used as the haptic control platform and integrated with the PC. The Omni includes a boom-mounted control that supports 6-degree-of-freedom (DOF) movement and 3 DOF force feedback. PHANTOM haptic devices have been used previously in industrial assembly simulations [3,5]. The interface automatically recorded participant performance data.

Figure 2. VR-BD apparatus including Omni Haptic Device with stylus control.

The software features included a virtual tabletop divided into two parts, including a display area and a work area. The display area presented the stimulus design patterns to be replicated by a participant. The work area was used for arranging the virtual blocks (see Figure 1, right side). The work area and blocks were presented at approximately 70% of actual size to allow the design pattern and workspace to be viewed on a 21-inch stereo monitor. All BDs were constructed with the aid of a target grid, which appeared as a 2x2 or 3x3 collection of squares in the work area, depending on the design stimulus. The Omni haptic device was used to manipulate a cursor (small blue orb) appearing on the display during BD training. Blocks could be grasped by touching the cursor against them and pressing the button on the control of the haptic device. A block could then be lifted from the table surface and rotated about any axis using the haptic control. Haptic features were included in the simulation to represent the blocks and the table as solid objects.

The type of control installed on the Omni was manipulated between participants as an independent variable (IV). Half the participants received VR training with the Omni stylus, as was used in the previous studies. The other half of the participant sample used the new custom block control (see Figure 3) designed to replicate the sensation of handling a real block, as in the native BD task.
2.2 Participants
Twenty-one participants between the ages of 20 and 54 (mean=27) were recruited for the study, including 12 female and 9 male participants. Conditions were not balanced for gender because past results [7] showed that testing and training were not sensitive to gender differences. All participants were required to have 20/20 (or corrected to normal) vision and to exhibit right-hand dominance. Hand dominance was identified through a demographic questionnaire and confirmed using the Edinburgh Handedness Inventory [11]. Participants rated their previous LEGO experience on a four-point scale ranging from “never” to “frequent.” The distribution of LEGO experience is summarized in Table 1.

<table>
<thead>
<tr>
<th>Past LEGO Use</th>
<th>Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequent</td>
<td>2</td>
</tr>
<tr>
<td>Moderate</td>
<td>6</td>
</tr>
<tr>
<td>Seldom</td>
<td>12</td>
</tr>
<tr>
<td>Never</td>
<td>1</td>
</tr>
</tbody>
</table>

Participants were required to complete all motor tasks as part of the experiment using their non-dominant (left) hand. This requirement was meant to simulate limited motor or assembly skill and to promote sensitivity of participant performance to the training conditions.

2.3 Procedure
There were four main parts of the experiment used for data collection: (1) an evaluation of baseline performance, (2) multiple training sessions in the native BD task, (3) VR training, and (4) post-test measurement of any performance improvement. The experiment was distributed across 8 days, as presented in Table 2. Each participant committed a total of 10 hours to the study.
Table 2. Experiment test and training schedule

<table>
<thead>
<tr>
<th>Day</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screening</td>
<td>• Demographic questionnaire</td>
</tr>
<tr>
<td></td>
<td>• Edinburgh Handedness Inventory</td>
</tr>
<tr>
<td>Day 1</td>
<td>• Assembly Task Baseline Testing</td>
</tr>
<tr>
<td></td>
<td>• Native WASI BD Training (4 trials)</td>
</tr>
<tr>
<td>Day 2</td>
<td>• Native WASI BD Training (4 trials) and Testing</td>
</tr>
<tr>
<td>Day 3</td>
<td>• Haptic device orientation (Dice manipulation training task and video training)</td>
</tr>
<tr>
<td></td>
<td>• VR Training (Basic with stylus control or block control; 3 trials)</td>
</tr>
<tr>
<td>Days 4 - 7</td>
<td>• VR Training (Basic with stylus control or block control; 3 trials/day)</td>
</tr>
<tr>
<td>Day 8</td>
<td>• Assembly Task Post-Testing</td>
</tr>
</tbody>
</table>

During testing, each participant received an instruction book and 75 LEGO pieces and was provided with a brief demonstration (using a different LEGO model) of how to assemble the pieces and follow the instruction book. Each participant was required to construct the LEGO helicopter shown in the instructions (Figure 4). As with the BD training task, participants were asked to complete the assembly with the left hand. There was no time limit, but participants were encouraged to work quickly. Performance was measured by recording time-to-task completion (TTC) and errors made during construction.

![Figure 3. LEGO model completed for assembly task](image)

Training was facilitated through the VR-BD task with one of the two haptic control types (stylus or block). The experiment also included a Control group that received no training (baseline and post-testing only). Each participant was assigned to one condition, yielding a total of seven participants per condition. Each participant visited the research lab for five separate training sessions (except participants assigned to the Control condition), completing 15 BD trials in total (10 designs per trial, as required by the established WASI protocol). The combined duration of the five visits was approximately 5 hours.

Training in the native BD task was also included in the experiment design in order to ensure participant proficiency in the cognitive aspects of the task. The training was split across Days 1 and 2. (The Control group did not experience native WASI BD Training as well as Days 2-7 of the experiment.) In prior pilot tests, it was determined that participants reached asymptote (in terms of a native BD task score) after completing 8 training trials. Therefore, having participants perform eight BD trials (four on Day 1 and four on Day 2, to reduce fatigue effects) was expected to train participants in the cognitive aspects of the task, allowing the VR training trials to focus more on motor skill development.
2.4 Experiment Design
The independent variable was the experiment group with three levels, including: Block group, Stylus group, and Control group. Participants assigned to the Block group completed native task training and native post-task testing on Days 1 and 2 and all VR training trials on Days 3-7. Participants controlled the virtual blocks in the VR using the block control (shown in Figure 3). Participants assigned to the Stylus group also completed native task training and native post-task testing on Days 1 and 2 and all VR training trials on Days 3-7. Participants controlled the virtual blocks in the VR using the stylus control. Participants assigned to the Control group only completed the baseline assembly task on Day 1. They did not participate in native task or VR training. They returned on Day 8 for post-testing.

The dependent variables (DV) included TTC, errors made during construction, accuracy of the completed model and pieces remaining. These variables were consistent with performance measures collected by Hochmitz and Yuviler-Gavish [10]. Corrected errors were defined as pieces repositioned during model construction. Model accuracy was based on whether the completed model perfectly matched the instructions. Completed models were either accurate, or not accurate. Final error was the number of pieces not included in the final assembly. All 75 LEGO bricks were required to complete the model, so every remaining piece represented an error. (Participants were told to use every piece as part of the instructions.) Total assembly error (reported in the Results) was a combination of the three error measures. A sum was calculated based on the corrected and final error counts. Further, if a participant’s final error count was 0 and the model was not accurate at the end of assembly (i.e., model accuracy = “No”), a value of 1 was added to the total assembly error.

Based on the original time or errors, a percentage of improvement (POI) was calculated using the following formula:

\[
\text{Percent Improvement} = \frac{\text{Pre-Test Time} - \text{Post-Test Time}}{\text{Pre-Test Time}} \times 100\%
\]  

2.5 Hypotheses
As mentioned above, it was hypothesized (H1) that the block-shaped control would more realistically represent the movement constraints during the assembly task, compared to the stylus control. Therefore, participants completing VR training using the block control were expected to perform better (in terms of speed and accuracy) in the assembly task than stylus and control participants. It was also hypothesized (H2) that the VR-BD task training would improve assembly task performance (reduced TTC and Total assembly error) between baseline and post tests.

Results and Discussion
The (baseline) pre- and post-test data were analyzed to identify differences between training with the two types of haptic devices. A series of paired t-tests were conducted to investigate the potential improvement in test performance within each group. Considering the relatively small sample size for each experiment group (i.e., N = 7), a nonparametric version of the paired t-test, the paired Wilcoxon test, was also conducted to verify results. The pattern of the results was the same for the parametric and non-parametric tests; therefore, the parametric results are reported here. With respect to comparisons among the experimental groups, including the control, both the one-way ANOVA test and the nonparametric Kruskal-Wallis test were applied. Again, the pattern of parametric and nonparametric test results was consistent and, therefore, only the parametric results are reported. The results are presented in the following subsections.

Descriptive statistics (means and standard deviations) on participant performance in pre- and post-tests are summarized in Table 3 with presentation according to experiment group. Video recording of two participants failed during pre-test trials; therefore, only data for six participants was used to determine Total assembly errors for the Block and Stylus groups (seven participants were used for the Control group). The remaining performance measures were not affected.
**Table 3. Assembly pre- and post-test results by condition, including standard deviations**

<table>
<thead>
<tr>
<th></th>
<th>Test</th>
<th>Block group</th>
<th>Stylus group</th>
<th>Control group</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Assembly time (min)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-Test</td>
<td>24.8 (10.8)</td>
<td>21.4 (9.2)</td>
<td>22.2 (3.5)</td>
<td></td>
</tr>
<tr>
<td>Post-Test</td>
<td>17.8 (8.9)</td>
<td>16.5 (4.5)</td>
<td>16.7 (2.9)</td>
<td></td>
</tr>
<tr>
<td><strong>Total assembly error</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-Test</td>
<td>4.0 (1.9)</td>
<td>3.7 (3.4)</td>
<td>4.4 (1.7)</td>
<td></td>
</tr>
<tr>
<td>Post-Test</td>
<td>1.2 (1.5)</td>
<td>1.7 (1.9)</td>
<td>1.6 (1.8)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5 presents the TTC results for the baseline and post-tests. The trends reveal the degree of improvement in assembly times for all groups. From the graph, it appears that greater improvements may have resulted from training with the block control; however, post-test performance was not as good as with the stylus or in the native task. On average, the participants in the present study took 22.8 min to complete the assembly task at baseline. This time decreased to an average of 17.0 min during post testing. For the participants in Hochmitz and Yuviler-Gavish’s [10] study, on which the current assembly task was based, the average completion time for the control group was 19.7 min.

Figure 6 presents the total assembly error for the baseline and post-tests. It can be seen that the average total assembly errors decreased for all groups. The Block and Control group participants appeared to improve at similar rates, with the Block group yielding a lower average number of errors, while participants receiving training with the stylus may not have improved at the same rate as the other participants.
Participant baseline performance between groups was compared using one-way ANOVA tests. Results revealed no significant effect of group on baseline assembly TTC \( (F(2, 18) = 0.32, p = 0.73) \) or total errors \( (F(2, 16) = 0.16, p = 0.85) \). These findings suggested that participants in all three groups started the tests at comparable skill levels; however, it can be noted that the Block group was slower, on average, across both baseline and post-training testing. The assembly task post-test results revealed improvements from baseline performance for all three groups. However, the reduction in assembly TTC was only significant for the Block and Control groups (see Table 4). For the Stylus group, the decrease was marginally significant \( (p<0.10) \). All three groups showed significant reduction in total assembly errors. Results are summarized in Table 4.

Table 4. Comparison of assembly task completion time and error

<table>
<thead>
<tr>
<th></th>
<th>Block group</th>
<th>Stylus group</th>
<th>Control group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly time</td>
<td>( t(6) = 6.98, p &lt; 0.001^* )</td>
<td>( t(6) = 1.51, p = 0.09 )</td>
<td>( t(6) = 10.04, p &lt; 0.001^* )</td>
</tr>
<tr>
<td>Total assembly error</td>
<td>( t(5) = 4.33, p = 0.004^* )</td>
<td>( t(5) = 2.74, p = 0.02^* )</td>
<td>( t(6) = 10.95, p &lt; 0.001^* )</td>
</tr>
</tbody>
</table>

After verifying the improvement in test performance within groups, further analysis was conducted to detect any potential differences in POI (percentage of improvement) for the TTC response between experiment groups by using a one-way ANOVA model. The analysis revealed no significant difference \( (F(2, 18) = 1.05, p = 0.37) \). This finding suggested that the degree of change in assembly task performance was similar among the training conditions. The same analysis was performed on the POI (or reduction) in assembly errors revealing no significant difference among groups \( (F(2, 16) = 0.66, p = 0.53) \). Although not statistically significant the Block group yielded a higher average POI in assembly errors \( (76.3\%) \) as compared to the Stylus group \( (55.2\%) \) and Control group \( (71.1\%) \).

In general, the results were consistent with expectations. Significant improvements were identified in assembly test performance based on the VR-BD task training, supporting H2. Participants showed improvement in assembly task TTC and errors under both VR training conditions, as well as the control condition. However, improvements in task completion time were only significant for the Block and Control groups but not the Stylus condition. Furthermore, the Block group produced greater improvements in assembly accuracy than both the Stylus and Control groups. These results were in partial support of H1 that the block control interface, resembling the training task objects, would provide some benefit to performance. While training with the block control had similar effects to the control group in terms of TTC, the lack of significant improvement following stylus training suggests training with an incompatible device may lead to negative transfer.
Conclusion

The objectives of this work were to determine whether haptic VR training conditions would benefit learning of an industrial assembly task and if a realistic haptic control design would lead to benefits in training performance. The assembly task results revealed the influence of VR simulation of simple psychomotor task training on occupational performance. Based on the results, VR-based training incorporating a control causing hand postures and motions similar to those used in the target task appears to be effective for training assembly tasks.

Future work in this area includes additional enhancements in the design of haptic controls for VR motor task simulations. For example, while the block control tested in this study replicated tactual aspects of actual blocks used in the native form of the task, there was an important difference in control vs. actual block movement. The block control was installed on the Omni haptic device platform as close as possible to the point of rotation, but not in the exact center. Therefore, while left and right rotations of the control were identical to handling of actual blocks, rotations about the other two axes required a slight circular rotation around an axis external to the block interface. This control gap represents a limitation of the current design. Another limitation of the present study was the lack of a training group exposed to only the native training condition for comparison with the VR conditions. The present work compared haptic stylus and block controls. However, use of a pure native task training condition as a control (which was done in previous studies [7]) would have provided additional context for the results.

Finally, while the results revealed significant differences among the VR and control conditions, there were no provisions in the participant instructions that would prevent them from participating in further motor skill training in between sessions. There was a minimum 10 day period in between pre- and post-testing for the Control group. However, it is unknown whether the participants engaged in activities that may have assisted or hindered their post-test performance.

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References

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