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While training participants to assemble a 3D wooden burr puzzle, we compared results of training in a stereoscopic, head tracked virtual assembly environment utilizing haptic devices and data gloves with real world training. While virtual training took participants about three times longer, the group that used the virtual environment was able to assemble the physical test puzzle about three times faster than the group trained with the physical puzzle. We present several possible cognitive explanations for these results and our plans for future exploration of the factors that improve the effectiveness of virtual process training over real world experience.

Keywords

Industrial & Manufacturing Systems Engineering, assembly, virtual reality, training, haptics, cognition

Disciplines

Computer-Aided Engineering and Design | Graphics and Human Computer Interfaces

Comments

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While training participants to assemble a 3D wooden burr puzzle, we compared results of training in a stereoscopic, head tracked virtual assembly environment utilizing haptic devices and data gloves with real world training. While virtual training took participants about three times longer, the group that used the virtual environment was able to assemble the physical test puzzle about three times faster than the group trained with the physical puzzle. We present several possible cognitive explanations for these results and our plans for future exploration of the factors that improve the effectiveness of virtual process training over real world experience.

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Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O; J.6 [Computer-aided Engineering]: Computer-aided manufacturing

1 Introduction

The introduction of new manufacturing assemblies in a product line presents significant challenges to industry. Significant time and cost can accumulate due to the need for retooling assembly line areas, training workers on the new assembly, and potential loss of materials during training. The cost of product redesign if a problem is discovered that requires changes to the assembly process can be considerable. By utilizing a virtual reality system that can import standard CAD models, we believe that unanticipated cases can be reduced since manufacturers will be able to train assembly workers virtually on the new assembly and reduce the loss of time and materials from failed assemblies [2]. The virtual training approach assumes that the learning experience can be segmented into the hand-eye motor component of learning and the cognitive procedure component, i.e., that net learning gains can be realized even if the virtual environment lacks some affordances of the real world. This assumption will be explored in this research. While some benefits are unlikely to be fully realized in simple assemblies, easily converted assembly lines, or when material goods for assembly training are inexpensive, the results presented in this paper provide some indication of the potential return on investment of virtual assembly training.

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While recent research in virtual reality training systems (VRTS) has focused on the inclusion of artificial intelligence (AI) to provide indicators of errors and assistance to the trainee [10], such systems are time consuming to train and require a greater investment in resources that is less appropriate in more agile assembly environments. To ensure that a training system can work in an agile manufacturing environment, the system must allow easy importation of any set of parts that can be assembled and facilitate training on the procedural steps that can be learned while the line is rearranged for the new assembly. Such a training system, while narrowly focused, may lead to reduced costs of getting the new line up to full efficiency as soon as it becomes operational.

2 Background

Industry practice has found a place for virtual assembly that results in a good cost-benefit equation and improves the overall process [9]. Recent research has also indicated that individuals prefer virtual training second only to master-apprentice training and choose to use it more often than other traditional forms of training [4]. Several studies have been conducted examining the effectiveness of virtual reality (VR) training, with one such study indicating that immersive training leads to improved performance on the real task vs. traditional 2D instructions [3]. Furthermore, research has shown that VR enhances training for simple assembly tasks, such as a peg into a hole, although the time taken for assembly in a virtual environment is roughly twice as long as a real assembly [8]. More complex assemblies, such as a Lego biplane, have been shown to take three times as long to assemble virtually, although transference of learning in the virtual training group is improved over that of a group that views a training video [1]. 6-degree of freedom (DOF) systems such as SPIDAR [16] has shown the efficacy of haptic systems, especially in improving placement accuracy of parts.

Unlike previous research that focused primarily on user preferences, compared passively viewing instructions vs. virtual assembly, or used cognitively simple assemblies, this study fills a gap in previous work by exploring a cognitively complex assembly (wooden burr puzzle) and comparing the learning transference of virtual vs. real training based on training times and actual assembly of the physical puzzle after training. A bimanual task in particular was picked because most real-world manufacturing tasks have workers using both hands. Like users of SPIDAR [5], there was a learning curve associated with using the devices.

3 Hardware and Software Environment

This study utilized an application called SPARTA (Scriptable Platform for Advanced Research in Teaching and Assembly). It combines VRJuggler [17] for stereoscopic immersion, OpenSceneGraph [14] for graphics, Voxmap PointShell™ (VPS) [11],[12],[13],[19] for physics for collisions between virtual objects, and VR JuggLua [15], which enables creating scenes and objects quickly using the Lua scripting language. Through VR JuggLua, SPARTA is able to utilize the Virtual Reality Peripheral Network (VRPN) software [18] to support a wide variety of hardware devices. In addition, SPARTA has driver support for some of the more popular haptic devices such as the PHANTOM

Figure 1 An image of the testing environment while in subassembly mode.

Omni® from Sensable. This haptic device, along with a 5DT Data Glove 5 Ultra, was used in the study.

The main haptics thread updates the devices and runs the physics calculations at 1000 Hz to ensure stability. The VPS method relies on collisions and force calculations between models composed of voxel elements. The reaction forces that are rendered do not include the part weight. A key element of the functionality in this study is the user is able to assemble a few parts and then group and move them together as one object. The SPARTA software calculates and uses 6-degrees of freedom (DOF) internally for forces and torques, however, the Omni haptic device is limited to rendering 3-DOF. Figure 1 shows the testing environment with a person editing the parts in the sub-assembly mode.

4 METHODS

A controlled lab experiment was conducted to evaluate the effectiveness of learning transfer from a stereoscopic haptic-enabled assembly environment to a real world assembly. A wooden burr puzzle was selected as the focus of the assembly task due to the cognitive difficulty of assembly without instruction and the simplicity of the six-step assembly. Ten participants (mean age of 20.6; SD=1.3) were recruited for this initial study and randomly assigned either to a control group who were trained using the physical blocks, or to the virtual condition, where participants were trained within the virtual environment. The groups were gender balanced with three males and two females per group. Based on a brief initial survey, there was no significant difference in computer experience or video game experience. However, a significant difference existed between groups in the number of engineering courses completed. None of the participants in the control group had taken an engineering course, while two of five participants in the virtual training group had completed two and three courses, respectively.

After obtaining informed consent, participants completed a paper-folding test of spatial ability [7] to control for variance due to spatial ability differences. Next, both groups of participants watched a five-minute training video explaining the virtual environment including instructions on the use of the haptic device and data glove. The stereoscopic display was a 120 Hz projector running at 1280x720 resolution rear projected onto a glass screen. Two PHANTOM Omni® haptic devices as well as two 5DT Data Glove 5 Ultra gloves, one each for the left and right hand, were connected. A virtual display of a hand is used to show the position and orientation of the glove. Each of the fingers in this display bends appropriately based on the bend values of the sensors in the device. An InterSense IS-900 inertial-ultrasonic hybrid tracking system was used to track the participant's head position and to provide the wand device for button input for entering and exiting subassembly mode. A Polhemus PATRIOT™ magnetic tracking system was used to track the position of the 5DT glove.

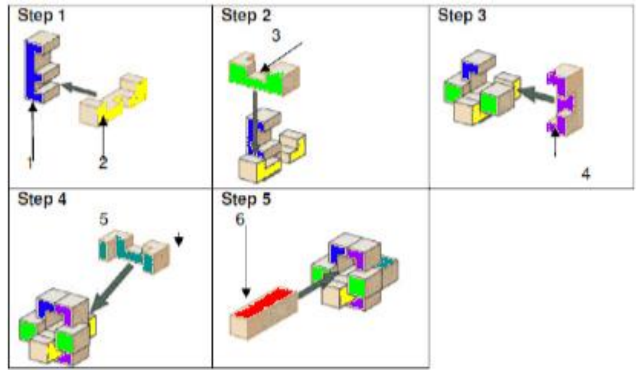
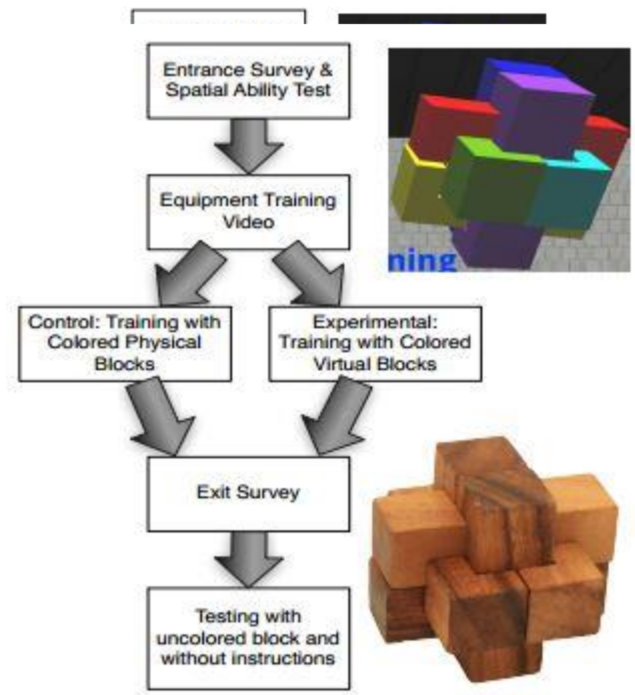


Figure 2 The colored assembly instructions that both groups used during the training phase.

During the training phase, all participants received a paper copy of the same color-coded set of instructions (see Figure 2). Those in the control group completed training by assembling the puzzle twice using wooden blocks with color-coded stickers. The virtual assembly group completed the puzzle twice using appropriately colored virtual blocks. Force feedback was provided through the Omni, however, no additional haptic guidance (snap-to, geometric constraints, etc.) was provided to assist in learning the assembly. Upon completion of the training phase, participants completed a short exit survey. Besides gathering information about the training experience, the exit survey also served as a distraction task to reduce the chance that test results would be dependent on short-term memory. Finally, participants completed assembly of the physical puzzle without color indicators or instructions. Completion time was recorded. An overview of these procedures can be seen in Figure 3.



5 RESULTS

The paper-folding test used to evaluate spatial ability has a score that can range from zero points (for no correct answers) up to twenty points. The virtual group had a mean spatial ability score of 13.2 (SD=2.588), while the control group had a mean spatial ability of 12.8 (SD=1.924). Since no significant differences were found in the spatial abilities between groups, we chose to analyze results using Student's T-Tests at the α=0.05 level rather than an ANCOVA with spatial ability as a covariant.

Figure 4 shows the training and testing times for both the virtual training group and control group. During the training phase, the control group completed the puzzle 3.63 times faster than the virtual training group based on the average of the two training points (p<0.001; effect size r=0.854). However, during the testing phase, the virtual training group completed the puzzle 3.84 times faster than the control group based on the average of the two points. In addition, the virtual training group completed the first test over 4 times faster than the control group, which serves as an indicator of superior learning transference. Due to high variances, the results for the testing time were not statistically significant (p=0.113); however, the effect size did indicate a medium effect (r=-0.3825), suggesting there is practical application of the finding.

Due to one participant in the control group spending 45 minutes on the first test assembly and potentially representing an outlier, we removed this data point from analysis and re-analyzed the results (see Figure 5). With this modification, the virtual training group completed the assembly of the actual puzzle 1.76 times faster than the control group. However, this result was not statistically significant (p=0.151) with a small-medium effect (r=-.331). Removing the outlier resulted in the groups being not equally balanced. Therefore, the data analysis after removing the outlier point may not be applicable; however, we chose to present them here to examine alternative explanations that might result from a fuller understanding of the data, given our low sample size.

It is also worth noting that none of the participants in the virtual training group failed to correctly complete the assembly during the testing phase; however, two participants in the control group failed to correctly complete the assembly. The failure rate between the two groups was marginally significant (p=0.071) with a medium effect size (r=-0.459). The improvement ratio from training to testing was 10.8 in the virtual group vs. 1.2 in the control group. With respect to analyzing overall time consisting of training and testing time, the virtual group was 1.5 times slower.

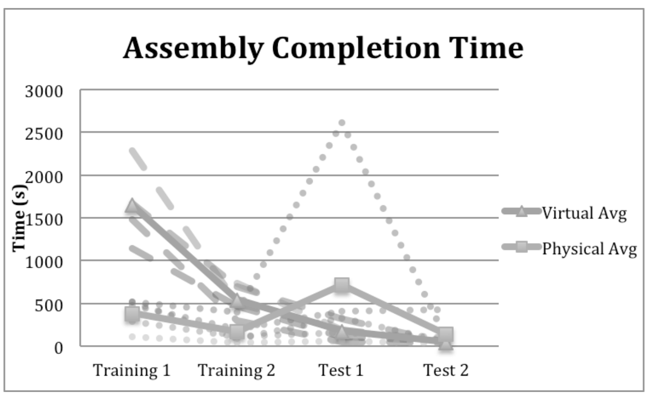


Figure 4 Graph showing individual virtual assembly training and testing times (dashed lines), control training and testing times (dotted lines), and average training and testing times for both groups (solid lines).

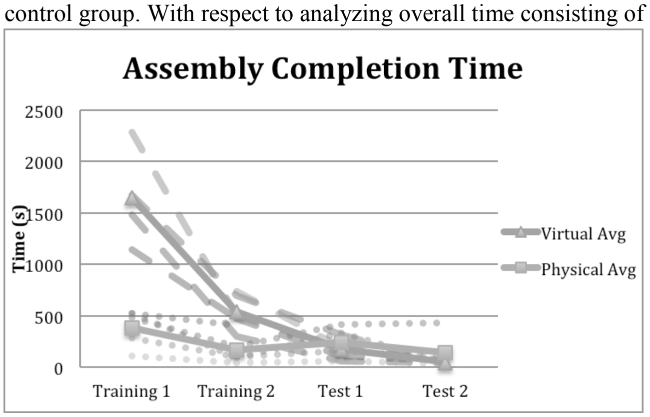


Figure 5 Graph of completion times with the outlier point removed.

On the exit survey, there was no significant difference between the control and virtual training group for ratings of task difficulty, realism, or helpfulness in learning the assembly. However, the control group rated the physical assembly process significantly (p=0.001) easier to use (mean=3.6; SD=0.548) than the virtual assembly group (mean=2.2; SD=0.447).

6 Discussion

While the results were mixed, several findings emerged that have practical implications and warrant further exploration.

First, participants performed better on the real world assembly task after virtual training in comparison with individuals who trained with the real world blocks. While this result was not significant, the effect size was reasonable and the p-value suggested that with a larger sample size, a significant value might be found. If these results do later prove to be significant, it will be surprising as it would suggest that users learn more by training in a virtual environment than they do when training on the physical task. However, several explanations may underlie this result.

The first of these is the easiest to evaluate: the increased training time for the virtual group may explain the higher transference of learning due to increased time of exposure to the assembly. To test this, in a future experiment the study could be designed to control for time by allowing participants to assemble the puzzle as many times as possible within a fixed time period.

The second explanation is somewhat counter-intuitive, namely that the increased difficulty of the task may improve individuals' learning. Because of the simulation aspect of the virtual assembly experience, and the use of unfamiliar interface devices (tracked glasses, gloves, haptic device, etc.), the longer training time that resulted in virtual training group may have indicated that the task was more difficult than training with the real blocks. On the surface this explanation may seem unlikely, since the difficulty of using new interface techniques requires greater cognitive resources than doing the assembly in a natural way; however, related recent research suggests that reading fonts that are more difficult to read increases retention [6]. This does provide some possible evidence that a greater demand on cognitive resources may lead to increased training retention.

A third explanation, supported by observation, is that participants in the control group focused on the secondary feature of color rather than the primary feature of shape during the training period. In the final test case, no blocks were colored and no assembly instructions were available. None of the participants in the virtual group made comments about the physical test puzzle lacking the colors from the instructions; however, two of the five members of the control group made these comments. Or perhaps there are aspects of the virtual environment that served to focus user attention on geometric features. Regardless of the effect of the virtual environment, this result may suggest that assembly procedure documentation for frequently assembled parts should not include indicators that dramatically differentiate pieces, which may detract from the trainee's ability to learn the procedure properly.

While we still need to determine the full cause of the difference in learning transference, another important finding from this study is that having industrial operators train using actual models may still be a more cost efficient method of training than virtual assembly and result in more accurate post-training assemblies. Producing a robust software solution that allows assembly engineers to import parts from CAD software effortlessly reduces the cost versus the time required to develop training animations, videos, or guided training via haptics. For assemblies where there are minimal cost implications beyond training time, the case appears to favor real world assembly. Operator labor and the cost of a missing operator on the line can be expensive, and while these results suggest that learning retention is higher in groups trained virtually, there was a significantly higher time cost in virtual training due to the nearly four-fold increase in training time. In the future, we plan to explore including ten minutes for participants to familiarize themselves with the virtual environment and the equipment through hands-on experience, rather than a video, in order to explore whether the large difference in training time is simply due to lack of familiarity with the virtual environment input devices. We expect that a timing difference will still exist but expect it to be closer to being two to three times longer, which is aligned with previous findings by both Gupta [8] and Adams [1].

Finally, one interesting point is that for the second trial in the testing phase, all participants in the virtual group completed it in 37 (two participants) or 53 seconds (3 participants); however, the control group completion time ranged from 32 seconds to 426 seconds (mean of 138.8 seconds; removing the highest time from the control group results in a mean time of 67 seconds). This provides some indication that the virtual group either had higher internal consistency or that virtual training leads to training saturation with fewer trials.

7 Conclusion

We have presented the results of a study examining the transference of learning from an immersive virtual reality-training environment versus real world training. These results indicate that training in a virtual environment leads to a reduction in real task completion time when tested. However, the training time to complete a cognitively complex assembly in a virtual environment is over three and a half times longer than the training time when using the physical components. Given the mixed results, this suggests that virtual assembly may provide benefits when part fabrication is expensive to offset the cost of additional operator time needed during the training phase.

These results have also led to several new research paths to increase the understanding of possible causes for the improved learning transference when training occurs within a virtual environment. We feel these future studies of time spent on task, effects of secondary part features (such as color), and effects of the interaction difficulty on learning retention will aid both the virtual learning community as well as the cognitive training community as a whole.

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