Comparative Effectiveness of Augmented Reality in Object Assembly

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ABSTRACT

Although there has been much speculation about the potential of Augmented Reality (AR), there are very few empirical studies about its effectiveness. This paper describes an experiment that tested the relative effectiveness of AR instructions in an assembly task. Task information was displayed in user's field of view and registered with the workspace as 3D objects to explicitly demonstrate the exact execution of a procedure step. Three instructional media were compared with the AR system: a printed manual, computer assisted instruction (CAI) using a monitor-based display, and CAI utilizing a head-mounted display. Results indicate that overlaying 3D instructions on the actual work pieces reduced the error rate for an assembly task by 82%, particularly diminishing cumulative errors - errors due to previous assembly mistakes. Measurement of mental effort indicated decreased mental effort in the AR condition, suggesting some of the mental calculation of the assembly task is offloaded to the system.

Keywords

Augmented reality, computer assisted instruction, human computer interaction, usability study.

INTRODUCTION

The term Augmented Reality (AR) is used to describe systems that blend computer generated virtual objects or environments with real environments [1, 2]. Unlike Virtual Reality (VR), AR enhances the real environment rather than replacing it. Graphics are superimposed on the user's view over the real environment. In a typical AR system, a see-through head-mounted display (HMD) is used to composite computer generated graphics with the real environment. AR technology has many potential applications, including computer assisted instruction (CAI) [3], industrial training [4], computer-aided surgery [5] computer visualization, engineering design, interior design and modeling [6, 7], and entertainment [8, 9].

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Research Problem

One of the most promising applications of AR is in increasing in productivity of manufacturing assembly, equipment maintenance, and procedural learning. The purpose of this research project was to explore the effectiveness of using AR as an instructional medium in computer-assisted assembly. It is commonly theorized that AR assistance in an assembly task will increase productivity and reduce errors due to the representation of the task properly registered with the workspace. Errors are less likely and the cognitive load of translating abstracted instructions onto reality is reduced.

This study has sought to provide three key contributions to our understanding of computer-human interaction with AR environments:

1. Does AR improve human performance in assembly tasks relative to other media?
2. What is a theoretical basis for how AR interfaces might provide cognitive support and augmentation?
3. Are there weaknesses in current AR interface design methodologies?

There has been much speculation about what AR can do, but very few empirical research studies exploring the effectiveness of AR. Even though a number of AR prototypes and test-bed applications have been developed, they are mainly "proof-of-concept" applications or demonstrations. Currently there is a lack of explicit theories and few detailed guidelines in computer-human interaction to support the design of this emerging technology and its varied applications.

OVERVIEW OF AUGMENTED REALITY IN ASSEMBLY PROCEDURES

We chose an assembly task because it epitomizes most issues and claims made about the benefit of AR in industrial plants, equipment maintenance, and scholastic instruction. The test assembly task combined the essential elements of AR computer assistance: (1) Spatial registration of virtual and real objects, (2) Interaction of virtual and real objects, and (3) The use of AR to sequence and coordinate human procedural action

An assembly task is representative of ways in which AR might guide and support many different classes of human action, and is an excellent test case for effectiveness.

The Importance of Manual Assembly and the Challenge of Customized Labor in Modern Manufacturing

Manufacturing processes generally consist of four operations: fabrication, assembly, inspection, and testing. AR can assist in all of them, but our research project focused on the mentally demanding assembly operation. While some assembly operations are automated, there are still a significant number of assembly operations that require human assemblers. Automated assembly is best for tasks that have well-defined locations for acquiring and inserting parts, and for manufacturing processes of mass production. In automobile assembly, the fabrication of body and chassis are typically automated, while the final assembly of interiors, trim, and lighting are manual. In a market where customization is key to competitiveness, the cost for redesigning automated processes can become substantial, whereas human workers are highly adaptable.

Manual assembly is also common in manufacturing processes where automation is not cost-effective, products are highly customized, or processes cannot be done by automatic machines (e.g. high quality soldering). A few examples include aircraft, product prototypes, medical devices, and aerospace contract works.

In the early 1990s, a new manufacturing conceptual framework, agile manufacturing, began to be employed widely. Agile manufacturing is a manufacturing operation that has the flexibility to quickly and efficiently adapt to match rapid changes in market demands. Agile manufacturing has resulted in mass customization of small quantities of highly specialized products and usually relies heavily on manual operations for flexibility.

One of the main problems in manual assembly is that expert assemblers are hard to train, particularly for assembly processes that require problem-solving skills. It often takes months or even years for a novice assembler to develop expert knowledge for assembling processes that have high complexity. In some cases, even the experts must constantly refer to the instruction manual for infrequently performed procedures or procedures with high complexity. In agile manufacturing, assemblers face the challenge of a continuously changing assembly process. It is impractical to re-train assemblers every time the assembly processes are changed. Assemblers need to be cross-trained to different assembly tasks so they have a deeper understanding of the process as a whole, and this training usually needs to be done on the job. So AR may have a significant impact on manufacturing industries by supporting human manual operations that might be needed in customized environments.

Augmented Reality for Computer Assisted Instruction: Theory and Hypotheses

CAI is typically used in complex assembly tasks that involve a huge set of assembly instructions, so the assembler can select the appropriate instructions online when needed. However, the limited sensorimotor bandwidth (i.e., amount of information flow between the user and a computer) of current computer interfaces make them inadequate for task engaged hands-free operation and continuous data access with high interface-user information transfer rates. The limitation of sensorimotor bandwidth of modern computer interfaces (i.e., small screens, limited input/output options, etc.) makes it difficult for the design to fully utilize the powerful capabilities of multimedia computer [10, 11]. Augmented reality systems may help in overcoming limitations of current interfaces by allowing information to be integrated into the environment and spatially registered with task objects. AR-based CAI provides unique human factors benefits as compared to approaches using traditional printed manuals or online CAI approaches.

AR reduces head and eye movement

In an AR environment, 3D synthesized computer graphics are overlaid in the user's field of view. A study conducted by Haines, *et al.* [12] indicated that pilots who use Head-up Displays (HUD) have less head and eye movement when compared to pilots that use Head-down Displays in the cockpit panels. By reducing head and eye movement and increasing eye-on-the-workspace time, user performance is expected to increase. By overlaying equivalent information on the work pieces in a spatially meaningful way, time for information searching in the instructional medium is reduced.

AR reduces the cost of attention switching

By "seaming" the information to the real environment, AR technologies could be used "as a complement of human cognitive processes" [13]. Using AR as an instructional medium can reduce the overhead of attention switching between the instructional medium and the task. AR systems can also be used to augment human attention. Synthesized computer graphics are merged with the user's view, so attention can be drawn by arrows, tags, object highlighting, animations, etc.

AR supports spatial cognition and mental transformation

AR technologies can also facilitate on-the-job training. Human beings tend to memorize information more effectively when they are "docked" to a frame of reference in the real world. Demosthenes, a Greek orator born around 384 B.C., used a strategy known as "Method of Loci" to memorize long speeches by mentally walking through his house, associating each element in the speech with different spots or objects in the house. In the field of neuroscience, there have been a number of theories suggesting a strong relationship between spatial location and working memory. Kirsh argued that "methods used to manage our space are key to organization of our thought patterns and behavior" [14]. By spatially relating information to physical objects and locations in the real world, AR provides a strong leverage of spatial cognition and memory [15].

Figure 1. The completed assembly task.

Hypotheses

If AR has the effect of significantly reducing head and eye movement and attention switching, assembly tasks should take less time with this medium. Therefore, we predict:

H1: When compared to traditional media, AR will significantly reduce the amount of time to complete an assembly task.

In assembly tasks, errors can be made by placing parts in a wrong location or incorrectly orienting parts. AR can reduce errors by eliminating locational ambiguity and explicitly indicating the orientation. Therefore, we predict:

H2: When compared to traditional media, AR will significantly improve accuracy and reduce errors of an assembly task.

When transferring attention back and forth between instructions and the locus of the action, the user must keep the operation, location, and orientation of the part in memory. Eliminating short-term memory demands by spatial superimposition, AR should decrease cognitive load. Therefore:

H3: When compared to traditional media, AR will significantly reduce the cognitive load of an assembly task.

METHODOLOGY

A between-subjects experiment was conducted. There was one independent variable, the class of instructional media used, with four levels: a printed manual (treatment 1), CAI on a Liquid Crystal Display (LCD) monitor (treatment 2), CAI on a see-through HMD (treatment 3), and spatially registered AR (treatment 4). The dependent variables included time of completion of the task, error rates, and perceived mental workload.

Participants

75 participants from an introductory undergraduate class at a university volunteered to participate in the study for class credit. None had previous experience in any AR environment. Because gender is correlated with spatial ability [16], participants were first approximately stratified by gender to control possibly gender effects. The average age of the participants is 21. 21 (28%) of the participants are female, and 54 (72%) are male.

Materials

Assembly task

Subjects were required to complete an assembly task according to the instructions presented using the specific medium as per the appropriate treatment. An assembly task based on Duplo blocks was used in the experiment to minimize bias towards a population with expertise in a certain knowledge related to an assembly task, and for task generalization so the result is applicable to general assembly tasks rather than assembly tasks in specific domains. The assembly task consisted of 56 procedural steps. For each step, subjects were required to acquire a part of a specific color and size from an unsorted part-bin and insert the part into the current subassembly in a specific position and orientation according to the instruction. The assembly task was 3 dimensional in nature; some steps required participants to put a part on top of parts that were previously inserted. Some steps were correlated, so a mistake made in a previous step could potentially generate additional mistakes in later steps. Figure 1 shows the completed assembly.

Stimulus materials: Instructional media format

Four treatments were created: printed media, CAI on a LCD monitor display, CAI on a see-through HMD, and spatially registered AR. All four treatments used pictorial representation, without language. The graphics used in all 4 treatments were rendered using the ImageTclAR Toolkit developed at Michigan State University [17]. Pictorial instructions in treatments 1, 2, and 3 are images from a static perspective viewpoint, and images in condition 4 are spatially registered with the real environment and rendered in real time according to the user's head position and orientation. In order to facilitate hands-free operation, subjects in treatment 2, 3, and 4 used voice commands to control the instructions. The voice command "next" prompts the instruction to the next procedural step, while the voice command "previous" prompts the instruction to the previous step. A human agent interpreted the voice command and controlled the instruction accordingly (with reaction time within a second) to ensure maximum accuracy on the voice recognition task. An audio signal was played as a confirmation of the voice command.

Treatment 1: Printed Media

The printed manual was single sided, with one procedural step per page (Figure 2a). The size of the diagram was 8.5" x 6". Subjects were free to move the manual to anywhere in the workspace, or hold it in their hand during operation.

Treatment 2: CAI on LCD monitor

Instructions were displayed in full screen on a laptop computer placed on the workspace (Figure 2b). The size of the LCD monitor is 15" (diagonal). Before the start of the experiment, subjects were free to adjust the brightness,

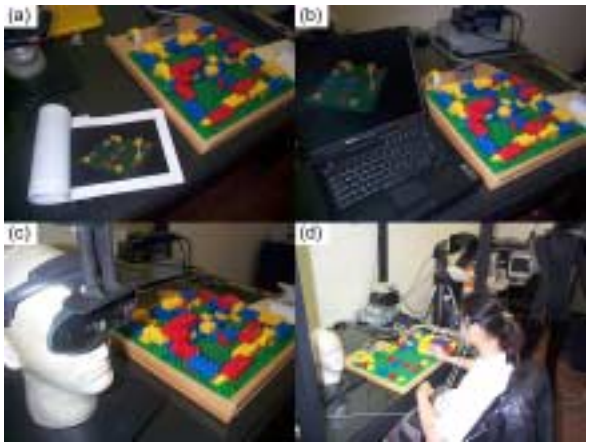

Figure 2. Experimental setups: (a) Treatment 1: printed media, (b) Treatment 2: CAI on LCD, (c) Treatment 3 and 4: CAI on HMD and AR, (d) experiment in action.

position and orientation of the screen.

Treatment 3: CAI on See-through HMD

Instructions were displayed on a see-through HMD. The see-through HMD was the Sony Glasstron LDI-100B (Figure 2c). It simulated a 30 inches (diagonal) screen at a viewing distance of 4 feet ahead. The display was modified to remove the liquid crystal shutter, significantly increasing the optical transmission of the display.

Treatment 4: Spatially registered AR

Instructions were displayed in stereo using the Sony Glasstron LDI-100B with the liquid crystal shutter removed. Subject head motion was tracked using a Polhemus Fastrak magnetic tracker. Stereo graphics were rendered in real time based on the data from the tracker. Figure 3 illustrates the user's view in the see-through HMD in treatment 4. The program was written using the ImageTclAR Toolkit [17]. The Toolkit uses a variation of the SPAAM algorithm for stereo display calibration [18].

Controlling variables: Luminosity, HMD weight, and calibration fatigue

In treatments 3 and 4, instructions were presented to the subjects through a see-through HMD. Light from the real world will be attenuated and distorted by the half-silver mirror when entering the HMD. The subjects' field-of-view (FOV) is limited by the HMD (Horizontal FOV is about 28 degree for the HMD). Also, people generally feel uncomfortable with a load on the head (The HMD weights about 120g). These are factors that count as disadvantages to performance in treatments 3 and 4. To control for these factors, participants in all treatments were required to wear the HMD during operation so that these variables remain constant among treatments. Also, 500 watts of additional illumination was cast onto the workspace so that the subjects could see the real environment clearly through the HMD.

In treatment 4, participants were required to perform a display calibration procedure that takes 8-12 minutes. This

Figure 3. Illustration of the views inside the see-through HMD in treatment condition 4.

procedure generally is considered to be challenging for an untrained user, and can potentially induce fatigue and mental workload factors to the assembly task that affect subject performance. To control for this factor, participants in all treatments were required to perform the display calibration procedure so that these variables remained constant among different treatments.

Measurements

Two types of measurements were taken: task performance and perceived mental workload. Task performance is defined as time of completion and accuracy of the task. Time of completion is the measurement of time to complete all 54 procedures. Accuracy is the measurement of the number of errors the subject made in the task, where an error is defined as: (1) a part is inserted at the wrong location and/or with the wrong orientation, (2) a part with the wrong color and/or wrong size is inserted, (3) a part is missing, or (4) an extra part is inserted. Two classes of errors are further defined: dependent error and independent error. Dependent error is an error that is related to another error made previously in the assembly steps. Independent error is an isolated error that does not relate to a previous step. Mental workload perceived by subjects is measured using the NASA Task Load Index (NASA TLX) [19]. Subjects rate each of the 6 categories (mental demand, physical demand, temporal demand, effort, performance, frustration level) based on their experience on the experiment using a 20 point scale. They were then asked to perform pair wise comparisons, indicating which category is more important correspond to the task among the 15 possible pairings. A mean weighted workload score is calculated by adding up the rating multiplied by an appropriate weighting for each category.

Procedure

Participants were first instructed about the display calibration procedure. The display calibration procedure involved aligning 9 crosshairs for each eye (18 crosshairs total) presented in the HMD sequentially to a crosshair located in the center on the workspace. After completing the calibration procedure, the experimenter explained the

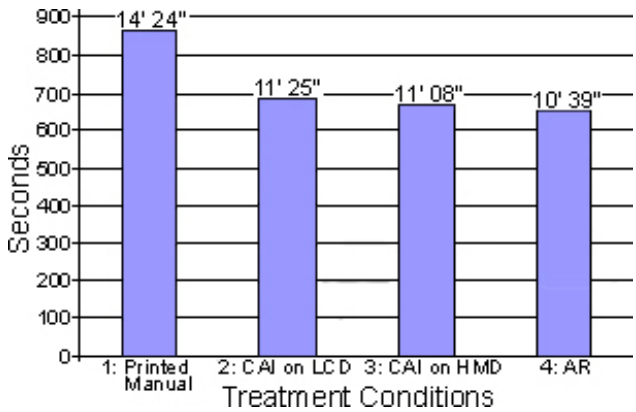

Figure 4. Average time of completion in each treatment.

graphical metaphors used in the instructions, and for treatments 2, 3, and 4, the voice command used to control the instructions. Participants then entered the pretest environment. Errors made in the pretest were explained to the participants. Participants were asked if they feel comfortable in performing the assembly, and if they want to repeat the pretest to get more familiar with the environment. When participants felt comfortable with the pretest environment, they were allowed to proceed to the main test environment. Participants were asked to perform the task as fast and as accurately as possible, and any questions the subjects had were answered at that time. The participants then completed the assembly task. Immediately after the experiment, participants completed the post-test questionnaires, including the NASA TLX rating, and demographic information.

RESULTS

Of the 75 participants, 18 were in treatment 2, and 19 in each of treatments 1, 3 and 4. An alpha level of 0.05 (2-tailed) was used for all statistical tests.

Descriptive Statistics

Figure 4 illustrate the mean time of completion for the assembly task. The table indicated that treatment 4 had the shortest time of completion, while treatment 1 had the longest time of completion. Figure 5 indicates the average number of errors for the task. The descriptive statistics reveal that treatment 4 has significantly lower error rates in all categories. They also indicated that the majority of errors in treatment 4 are independent errors, whereas treatments 1, 2 and 3 exhibit a majority proportion of dependent errors. Table 1 indicates the mean rating of the NASA TLX. The statistics show that subjects in treatment 1 have the highest mental workload, whereas subjects in treatment 4 have the lowest mental workload.

Effect of Instructional Medium on Time of Completion

A one-way Analysis of Variance (ANOVA) was conducted on the effect of instructional medium on time of completion. The effect of time of completion depending on the instructional medium is statistically significant, $F(3, 71) = 3.75$, $p = 0.015$. Post hoc comparisons were further conducted to obtain all possible pair wise comparisons

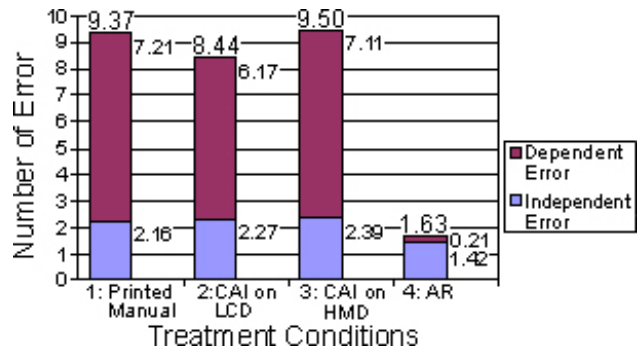

Figure 5. Average number of error in each treatment.

Treatment Condition	NASA TLX Rating
1: Printed Manual	13.3 / 20
2: CAI on LCD	12.2 / 20
3: CAI on HMD	11.0 / 20
4: AR	10.0 / 20

Table 1. Average score on NASA TLX rating in each treatment.

among treatments. The analysis shows that there is a statistically significant effect between treatments 1 and 4 ($p = 0.019$). The effect between treatments 1 and 2 and treatments 1 and 3 trends toward significance ($p = 0.085$ and 0.092 respectively). But there is no significant effect between treatments 2 and 3 ($p = 1.000$), treatments 2 and 4 ($p = 1.000$), and treatments 3 and 4 ($p = 1.000$). The results of the ANOVA analyses show that treatments 2, 3 and 4 have a significantly shorter time of completion comparing with treatment 1. But there is no statistically significant effect between treatments 2, 3 and 4. Hypotheses H1 is not supported; AR does not appear to have an advantage in time of completion comparing with other traditional media.

Effect of Instructional Medium on Accuracy

Effect of Instructional Media on Total Errors

A one-way ANOVA was conducted on the effect of instructional medium on total error rate. The effect is statistically significant, $F(3, 71) = 4.41$, $p = 0.007$. Post hoc comparisons were further conducted to obtain all possible pair wise comparisons among treatments. The analysis shows that there are statistically significant effects between treatments 1 and 4 ($p = 0.019$) and treatments 3 and 4 ($p = 0.012$). The effect between treatments 2 and 4 trends toward significance ($p = 0.073$). But there is no significant effect between treatments 1 and 2 ($p = 1.000$), treatments 1 and 3 ($p = 1.000$), and treatments 2 and 3 ($p = 1.000$). The results of the ANOVA analyses show that treatment 4 has a significant improvement in total error comparing with treatments 1, 2 and 3. However, there is no statistically significant effect between treatments 1, 2 and 3.

Effect of Instructional Media on Dependent Error

A one-way ANOVA was conducted on the effect of instructional medium on dependent error. The effect of dependent error depending on instructional medium is statistically significant, $F(3, 71) = 4.68$, $p = 0.005$. Post hoc comparisons were further conducted to obtain all possible

pair wise comparisons among treatments. The analysis shows that there are statistically significant effects between treatments 1 and 4 (p = 0.017) and treatments 3 and 4 (p =0.009). The effect between treatments 2 and 4 trends toward significance (p = 0.070). But there is no significant effect between treatments 1 and 2 (p = 1.000), treatments 1 and 3 (p = 1.000), and treatments 2 and 3 (p = 1.000). The results of the ANOVA analyses show that treatment 4 has a significant improvement in dependent error comparing with treatments 1, 2 and 3. However, there is no statistically significant effect between treatments 1, 2 and 3.

Effect of Instructional Media on Independent Error

A one-way ANOVA was conducted on the effect of instructional medium on independent error rates. The effect of independent error depending on instructional medium is not statistically significant, $F(3, 71) = 0.967$, $p = 0.413$.

In general, Hypothesis H2 is supported; instructional medium appears to have a significant effect on error rates.

Effect of Instructional Medium on Mental Workload

A one-way ANOVA was conducted on the effect of instructional medium on the NASA TLX rating. The effect was statistically significant, $F(3, 71) = 6.26$, $p = 0.001$. Hypotheses H3 is supported; type of instructional medium appears to have an effect on mental workload.

DISCUSSION AND CONCLUSION

This section explores the experimental findings in relationship to the stated hypotheses. It investigates the implications of the results on the theoretical model, and provides further insight into the influence of AR in human performance and perception.

Effect of Information Overlay on Performance

By overlaying information in the user's view using a see-through HMD, task performance is expected to increase by reducing head and eye movement between the workspace and the detached medium. So performance in treatments 3 and 4 is expected to be better than treatments 1 and 2. Even though there are statistical significant advantages in performance in treatment 4 comparing with treatments 1 and 2, there is no significant advantage in time of completion in treatment 3 comparing with treatment 2, and in accuracy in treatment 3 comparing with treatments 1 and 2. Treatment 3 does not receive the advantage of information overlay as expected.

In treatments 1, 2 and 3, we observed that a common practice among subjects was to count the number of bumps from the edge of the Duplo base plate to determine the exact position of the part to be inserted. Some subjects in treatment 3 also reported that it was hard to count bumps on the instructions, since they could not touch the instructions physically. There was evidence that the possible advantage of overlaying information on the workspace may have been negated by the cost of visual interference. Some subjects in treatment 3 reported that the overlaid instructions interfered with the workspace, and it was hard to see the workspace. Conversely, others stated that the workspace interfered with the overlaid instructions, and it was hard to read the instructions. This is consistent with studies of HUDs for automobile drivers indicating that symbology placed within a 5 degree radius of the fovea is annoying to drivers [20, 21].

The Sony Glasstron HMD projects a simulated 30” (diagonal) screen at 48” in front of the user's view. The distance between the subject’s head and the top of the workbench is approximately 18”. Therefore, the projected image in the HMD appears to be under the workbench. Some of the subjects in treatment 3 reported that it is hard to adjust the focus to a point under the workbench. Some of the subjects moved their heads up and looked at a plain background on the wall when they read the instructions to solve the visual clutter and/or focusing problem. This portion of subjects gained no advantage from increasing eye-on-the-workspace time by overlaying information.

The performance result and the reports of participants suggest that overlaying information in the central vision area of the user’s view does not facilitate improvement in human performance. However, based on the limitations of FOV and resolution of the current HMD technologies, only a very limited amount of information can be placed outside of the central vision area of a user.

Effect of Attention Switching and Mental Transformation Offloading on Performance

By reducing attention switching between instructional medium and workspace, performance in treatment 4 is expected to increase relative to treatments 1, 2 and 3. Performance in treatment 4 is also expected to increase by offloading the mental transformation tasks to the computer, where traditional pictorial instructions need to be mentally transformed to the subject’s point of view.

There is a statistically significant improvement in time of completion in treatments 2, 3, and 4 comparing with treatment 1, however, there is no statistically significant advantage in time of completion in treatment 4 comparing with treatments 2 and 3. We presume that this time advantage is resulted by hands-free operation using voice command in treatments 2, 3, and 4, whereas subjects in treatment 1 need to flip the paper instructional manual while they are performing the task. However, there is a statistically significant improvement in accuracy in treatment 4 compared to treatments 1, 2, and 3. Therefore, there is an overall performance improvement in treatment 4 comparing to treatment 1, 2 and 3.

There is extensive research in HUD ergonomics for aircraft pilots with particular examination of the issue of attention switching among information sources and the environment. Several reports indicate that optically overlaid information cannot be processed in parallel [22-24]. Others have reported that there is a time cost associated with cognitive switching among the environment and the [25-27].

In AR, synthetic computer graphics are registered with the real world and appear to be a part of the world. This eliminates the cognitive load of switching attention among the instruction and the working environment. Although we are not aware of studies about how computer-assisted mental transformation of pictorial diagram affects user performance, we theorized that computer assistance in mental transformation and the minimizing of attention switching will result in improvement of performance. While it is likely that both contributed to the improvement in the AR condition, we cannot determine how much each of these two factors contributed to user performance individually. More research is needed to determine the contributions of these factors.

Effect of Instructional Medium on Mental Workload

We hypothesized that mental workload of the assembly task using AR instruction is lower than that for traditional instructional media. Using the NASA TLX measurement of mental workload, participants reported that the AR condition was less mentally demanding. The finding is consistent with the theory that AR may reduce the amount of mental manipulation of object location. If participants did not have to mentally transform objects and keep a model of the relationship of the assembly object to its location in the working memory, they would experience less mental workload.

Effect of Instructional Medium on Dependent Error

The study found that participants who used the AR system made far fewer dependent errors. This strong advantage of AR systems may be due to the fact that determining position and orientation from pictorial diagrams drawn from the author's perspective is a primitive mentally demanding task. Human beings tend to approximate position and orientation using fixations and landmarks already in place. In some cases, assemblers use parts inserted in previous steps as fixations and landmarks to determine the position and orientation of the part in the current step. By overlaying instructions to the exact position of the part to be inserted, AR not only reduces the cognitive load of locating the position and orientation at the workspace, but also eliminates reliance on potentially erroneous landmarks. In cases where landmarks are the results of previous assembly steps, correct location cues provided by an AR system prevent cascading of errors and reduce error interdependency among steps. The lowering of dependent errors and the support of AR for spatial error correction may have important implications for real world assembly and procedural learning.

Effect of Attention Tunneling in Augmented Reality

We observed that participants using an AR system corrected mistakes made in previous assembly steps far less frequently than participants using traditional instructions. This observation is consistent with the phenomenon of attention tunneling. Attention tunneling occurs when user's attention is focused on the area cued, at the cost of other areas. Important information in the area outside the cued area may be missed, while this information might have been detected in the absence of the cueing. Dopping-Hepenstal reported that "military pilots fixated more frequently on information presented on a HUD at the cost of scanning the outside scene" [28]. Yeh, et al. reported that "cueing aided the target detection task for expected targets but drew attention away from the presence of unexpected targets" [29]. Attention tunneling can reduce user performance and generate potentially hazardous scenarios. Yeh et al. recommended that the designer of such cueing systems more carefully evaluate operator reliance on automation and the potential cost on performance when information from the environment must be attended to for optimal performance.

Conclusion

This study provides evidence to support the proposition that AR systems improve task performance and can relieve mental workload on assembly tasks. The ability to overlay and register information on the workspace in a spatially meaningful way allows AR to be a more effective instructional medium. However, the limitations in the current calibration techniques and display and tracking technologies are the biggest obstacles preventing AR from being realistic in practical uses. Designers seeking to make use of the performance gains of AR systems also need to consider how the user manages their attention in such systems and avoid over-reliance on cues from the AR system. The phenomenon of attention tunneling could possibly reduce performance in cases where AR cueing overwhelms the user's attention causing distraction from important relevant cues of the physical environment.

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