AN EVALUATION OF THE TRAINING EFFECTIVENESS OF VIRTUAL ENVIRONMENTS

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ABSTRACT

During the Boeing Joint Strike Fighter Concept Development Phase, we investigated the feasibility of using three-dimensional (3D) solid models, implemented within a Virtual Environment (VE), as a low-cost partial replacement for conventional hardware mockup trainers for aircraft maintainers. Currently, there are few studies directly comparing performance using VE-based training to more conventional methods. This paper summarizes the results of several empirical studies conducted to evaluate the effectiveness of aircraft maintenance training within VEs. In these studies, trainees were taught a simple remove-and-replace maintenance procedure. The task, while not complex, required a number of ordered steps involving visual and physical obstructions. Training effectiveness was assessed with a written test of task procedures and with an objective assessment of task performance on a hardware mockup. Measures of performance included task completion time and procedural errors (e.g., incorrect action, wrong tool). The initial study compared hardware mockup training to two alternative display formats: solid model-based VEs and 3D line drawings implemented as computer-based displays (CBD). Within each of these display formats, we compared passive “hands-off” training with user-interactive training. Results of the study indicated that as realism in the virtual training environment increased, performance approached that achieved with the more costly, time-intensive hardware mockup training. Another study assessed immersive Virtual Reality (VR) for task training. Participants in this condition trained for the maintenance task in an immersive VR, wearing a head-mounted display and interacting with task components using a 3D mouse. Results indicated that training time for the immersive condition was longer than the other CBD training methods, with a diminished task performance. Finally, using participants from the initial training study, we addressed the effectiveness of using VEs for maintenance rehearsal three months after completing initial training. Rehearsal involved a review of the task using one of two CBD methods. The first rehearsal condition was a review with annotated technical drawings; the second was the solid model-based interactive VE. A third group, the control, had no rehearsal. Performance for all participants was evaluated as before – with a written test of task procedures and performance on the hardware mockup. Results of this study showed a trend for better performance after interactive VE rehearsal over that of the other two conditions. Collectively, these studies indicate that solid model-based VEs provide a potentially significant alternative to hardware mockup based training, resulting in savings in training time and cost. Further research is needed to identify the types of training scenarios for which VEs are most effective..

ABOUT THE AUTHORS

Dr. Barbara Barnett has had twelve years of human factors experience at Boeing, both in applied research and advanced design applications. Her primary focus has been in the areas of workload prediction and assessment, modeling pilot performance and decision-making, cognitive ability assessment, performance measurement, training transfer evaluation, and development of principles for decision aiding and display design. Her efforts have involved contractual and internal research and development, as well as direct support to aircraft programs. Currently, Dr. Barnett is an Instructional Designer with Boeing’s Informational and Technical Data Systems group. She is currently investigating the effectiveness of virtual environments for training as part of the Boeing Joint Strike Fighter (JSF) Maintainer-in-the-Loop Program.

Ms. Katrin Helbing has been with Boeing for eight years. During that time, she has had worked on defining and assessing requirements for a variety of human interface issues for both manned and unmanned vehicles. Her focus has been on conducting usability studies and defining visual, physical, training, and information requirements. She is currently an Instructional Designer with Boeing’s

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Mr. Glenn Hancock has worked at Boeing since 1977. With a background in computer science, he has provided application programming and computer support for human factors programs. His additional duties have included experimental design and analysis of human performance data, discrete event simulation and human anthropometric modeling. Mr. Hancock currently supports Boeing's Design, Manufacturing and Producability Simulation / Advanced Digital Enterprise Processes and Tools (DMAPS/ADEPT) programs performing Virtual Reality applications programming.

Mr. Raymond Heininger has over 15 years of combined experience in the field of supportability at Boeing. He spent 2 years as a logistics engineer on advanced aircraft programs, ensuring that supportability was considered in the design of the aircraft, and providing expertise for the handling and support of the aircraft. In addition, Mr. Heininger was responsible for the planning, costing, scheduling, and proposal preparation of all of the supportability demonstrations and supportability mockups. Mr. Heininger spent 7 years on the F-15 program as a support equipment engineer. For the past 5 years, Mr. Heininger has been responsible for the research activities relating to virtual reality technologies and advanced digital definition for supportability and design for Boeing's DMAPS/ADEPT programs. He is the principal investigator for a number of programs aimed at integrating virtual reality technologies into the IPD process for analytical verification of supportability, design, manufacturing, retrofit, and training products and processes on future aircraft projects.

Dr. Bruce Perrin is an Associate Technical Fellow, assigned to the Advanced Products area of Instructional and Technical Data Systems. Dr. Perrin has been employed at Boeing for over 14 years, during which time he has been responsible for the analysis, design, and development of training and decision support systems, and the conduct of formative and summative evaluations of them. He currently heads the JSF Training Management & Support System (TM&SS) concept definition effort and is the lead of the JSF Intelligent Agents for Performance Assessment project. Dr. Perrin's research interests and publications include work in the areas of cognitive analyses of training environments, expert systems for training and job-aiding, training system evaluation, adaptive training methods, and decision-making and -aiding under uncertainty.

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BACKGROUND

With cuts in military spending continuing, all aspects of aircraft life cycle are being examined with an increasing emphasis on value. One area which shows significant potential for cost savings was aircraft maintenance training. Currently, maintenance training includes substantial amounts of hands-on training on full-scale hardware trainers. Although thorough, this type of training is time consuming and costly. Often, such training requires that the student, the hardware, and an instructor be together in the same place at the same time. These trainers are expensive to build, are costly to modify as the aircraft matures, and must be maintained.

The Boeing Company is looking at using advanced computer technology, specifically virtual technologies, to reduce the number of hardware trainers necessary to develop and retain maintenance skills. Virtual technologies offer a broad range of potential advantages for aircraft maintainer training. Significant cost savings may be realized during trainer development through data sharing and importing 3D models from existing, engineering-created designs. With virtual trainers, maintainers can train anywhere, at any time, with fewer requirements for specialized equipment. Computer-based maintenance trainers are more portable and require less space than typical hardware mockups. Multiple trainees can be trained simultaneously on different virtual systems. Virtual trainers would allow for just-in-time training, ensuring faster turnaround rates and higher sortie generation. Finally, system upgrades, modifications, and configuration control are straightforward and inexpensive using virtual models, relative to their hardware counterparts.

The Boeing Company has conducted a series of studies to evaluate the efficacy of virtual maintenance training (VMT) for aircraft maintainers. Two specific types of advanced virtual technology were evaluated: virtual environments (VE) and virtual reality (VR). For our purposes, VE is defined as computer-simulated 3D environments displayed on a conventional computer monitor. Observers are able to obtain alternative 3D views using a mouse to control camera perspective. VR, on the other hand, is what is more typically thought of as an immersive condition, in which observers don a head mounted display and/or data gloves and are able to navigate through the virtual space.

The purpose of these studies was to collect concrete data to compare performance after hardware-based training to performance with different types of VMT. These studies were intended to provide an initial assessment of the effectiveness of virtual technologies for maintenance training, and therefore, suggest the direction that future VMT should take.

VE FOR MAINTENANCE TRAINING

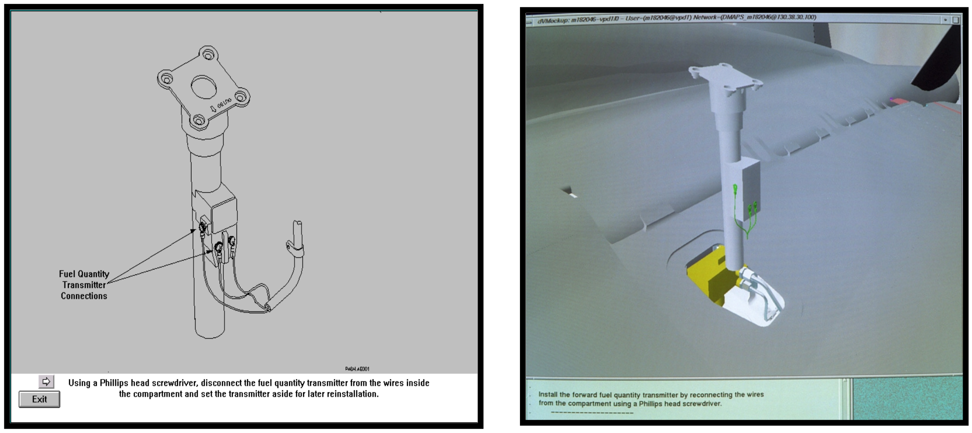
For the VE-based study described in this section, a set of five conditions was used to train a specific aircraft maintenance task. A description of these training conditions and the maintenance task follows.

Maintenance Task

The maintenance training task used in this study was the removal and replacement of an aircraft fuel valve. This 24-step procedure provided the appropriate amount of complexity, and imposed both cognitive and physical demands on the trainees. Physical and visual obstructions made this task ideal for virtual representation. The pre-existing computer models of the necessary parts aided in rapid development of the training and mockup materials.

Training Conditions

Five training conditions were established for this study: four computer-based training conditions and one mockup condition to use as a baseline comparison. All five training conditions had the same basic structure -- identical audio and written instructions were presented during training and the task procedure and sequence were the same for all training conditions. In all cases, progression through



(a) (b)

Figure 1. Computer-based display conditions: (a) Technical Drawing and (b) VE.

the training course was self-paced and a single pass through the training materials was allowed. The training courses differed only in the visual material presented to the trainees and the type of interaction the trainees had with the training materials.

Computer-Based Displays (CBD) Two types of computer-based display formats were tested: Technical Drawing and Virtual Environment conditions. The *Technical Drawing* format (Figure 1a) consisted of line drawings which were taken directly from the existing Interactive Electronic Technical Manual (IETM) illustrations for a fuel valve removal and replacement task. The relevant parts were highlighted with color or animation for emphasis.

The *Virtual Environment (VE)* format (Figure 1b) consisted of 3D models displayed on a computer monitor which were embellished with color, highlighting, shading, texture, and animation. The 3D models were created in Unigraphics, and converted to run in an interactive virtual reality authoring tool, dVISE, by Division. The VE displays were generated in dVISE on a Silicon Graphics Onyx.

The VE graphics were more realistic than the line drawings presented in the Technical Drawing condition. Also, the VE condition allowed for different camera views, enabling the trainees to "get in the environment" for a better view of the aircraft parts in question. The VE images were animated to show movements of parts throughout the training task (for example, the actual removal of the refuel pilot valve from the fuel compartment). As the relevant parts were moved, they were highlighted with color for emphasis.

The two types of display formats were presented with two interface methods. One interface method was *Passive*, that is, the trainee did not interact directly with the training material except to advance through the procedure. Trainees simply watched and listened to the training material. In the *Passive Technical Drawing* condition, all of the images were static, but significant parts were highlighted with color. In the *Passive VE* condition, in addition to color highlighting, images were animated to illustrate the removal and replacement task.

The second interface method, *Interactive* training, required the trainees to interact with the training material, therefore making them active participants in the learning process. In the Interactive conditions, trainees needed to "click" the mouse on the different parts to initiate animation of a given step. For example, if the task called for a bolt to be removed, the trainee was required to click on the appropriate bolt, at which point the computer animation showed the bolt move out of the hole. This interaction was essentially identical for both the Technical Drawing and VE display formats.

In each of these CBD conditions, trainees viewed a number of screens on which images of the task were presented. Each screen presented one step in the task. Trainees were encouraged to view a single screen as long as was necessary for them to learn the step. They could progress from one step to the next at will, but they were not allowed to return to previous steps. The audio instructions for a given step were played a single time, but identical written instructions were always displayed in a text box on the screen.

Hardware Mockup The Mockup training condition attempted to mimic current maintenance training procedures. It consisted of "hands-on" training on a full-scale mockup of the appropriate aircraft section, shown in Figure 2. The mockup was built from actual production models and drawings, using off-the-shelf hardware and simulated aircraft parts built to specifications from epoxy resin. The written and audio training instructions were presented via a computer, and guided the trainees through the steps of the task. In this condition, the experimenter acted as a coach, assisting the trainees in performing the maintenance task as they progressed through the training, and answering any questions they may have had. A door was provided on the side of the mockup through which trainees could look to get a better view of the inside of the fuel compartment. This door was later closed during testing.

Figure 2. Hardware mockup

Procedure

People who had previous experience with either aircraft maintenance or fuel systems were not included in the study. Participants were not pre-screened for skill or ability. Each participant was randomly assigned to one of the five training conditions.

At the beginning of the test session, each participant completed a short background questionnaire, followed by a paper and pencil test to assess their spatial visualization aptitude. This information was later used to statistically control an individual differences in mechanical skills and ability to process displayed information.

Participants were then given instructions specific to their training conditions and completed the training. The amount of time each participant spent in training was recorded.

After the training was finished, participants immediately completed a written test of their task knowledge. This information was used to assess how much each participant learned about the task during training. Some of the questions were detailed and specific, so that subtle differences in acquired knowledge could be determined.

The final step in the test session was completion of the training transfer task. During this phase, participants completed the training task on the full-scale hardware mockup without the aid of written or audio instructions for reference. They were asked to work as quickly and as accurately as possible, and to complete the steps in the order in which they were trained.

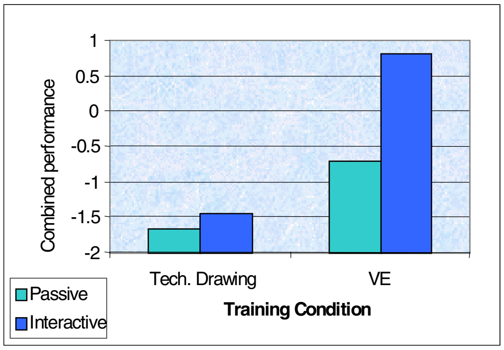
Performance Measures

A number of measures were collected during the study. Time spent on the training was recorded, as were knowledge test scores and transfer task completion times. Errors in task performance were categorized and recorded. The following actions were considered errors: omitted step, step out of order, incorrect action, wrong tool, forgotten procedure, major procedural errors (errors which would result in damage to the task components or would compromise the integrity of the aircraft flight). These error categories were later combined to distinguish important errors from minor, inconsequential errors. Errors which were considered to be important were: omitted step, incorrect action, forgotten procedure, and major procedural error.

Results

The possible impact of individual difference variables (i.e., mechanical skills and ability to process displayed information) was evaluated with analysis of covariance. Initial comparisons were made between the four computer-based display conditions, resulting in a 2 X 2 comparison of Display Format and Interface Method. Planned tests of differences between least squared means were used to compare individual treatment conditions. These results are summarized in Figure 3. The most telling results were in the combined performance scores, where errors, task time, and knowledge test scores were converted to z-scores and combined into a single measure (Figure 3a). Significant differences were found between the two Display Formats ($F = 10.01$, $p = 0.0033$).

Specifically, the trainees in the VE condition scored higher in combined performance than the Technical Drawing trainees.



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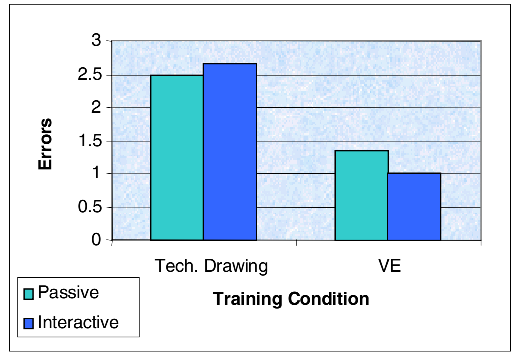

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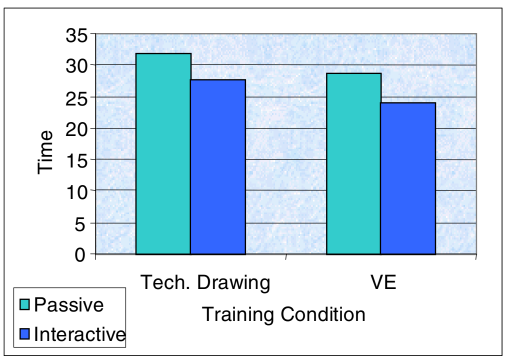

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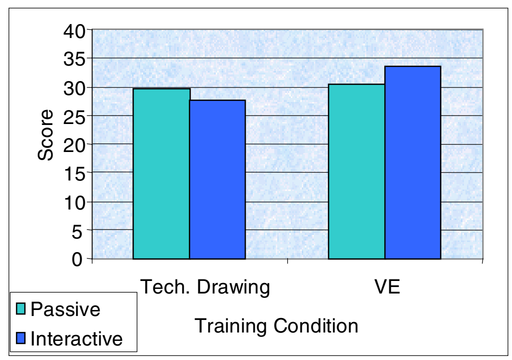

(d)

Figure 3. Results of Display Format by Interface Method Analyses.

Better performance in the VE condition was also evident in the analysis of important errors (Figure 3b). The trainees in the VE condition had significantly fewer important errors than trainees in the Technical Drawing condition ($F = 5.41$, $p = 0.0261$).

A significant difference in training transfer task time was also found in the Interaction Method – Passive vs. Interactive training. The Interactive training condition produced significantly faster performance times that the Passive training condition ($F = 6.44$, $p = 0.0159$), as shown in Figure 3c.

In addition, a significant interaction was found between Display Format and Interface Method for the knowledge test scores conditions ($F = 4.77$, $p = 0.0359$). As illustrated in Figure 3d, test of mean differences revealed that the Interactive VE trainees scored significantly higher on the knowledge test than trainees in the other three computer-based display.

As mentioned previously, a main effect of CBD training groups in a 2 X 2 analysis showed significantly better performance for VE training over Technical Drawing training. However, Figure 4 illustrates that participants who trained on the mockup still had better combined performance than any of the CBD groups, with the exception of the Interactive VE ($F = 8.00$, $p = .0001$). This trend was repeated for all performance measures.

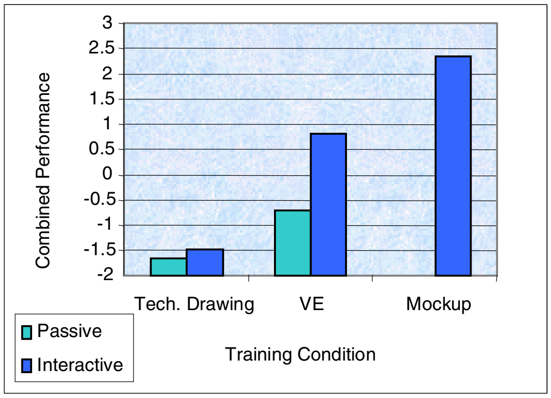

Figure 4. Combined performance – CBD vs. mockup.

Significant differences were found in the amount of time needed to train on the different training conditions (F = 193.22, p = .0001). The mockup training condition required significantly more time to complete than the four CBD conditions. This effect is shown in Figure 5.

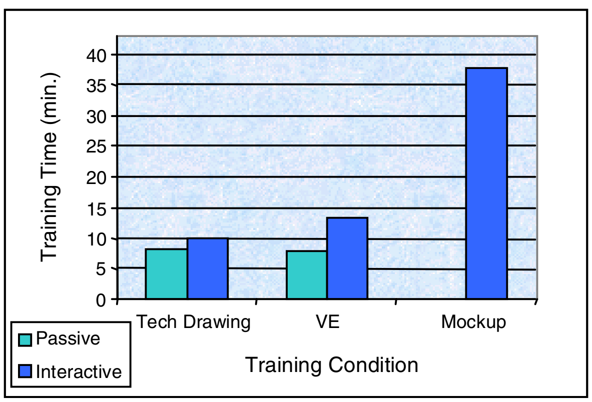

Figure 5. Training time.

Finally, it should be noted that there is an issue of common methods contamination. Participants who completed the Mockup training did so on the same piece of hardware that was later used for the testing portion of the study. Ideally, the training and testing would have been conducted on two different pieces of hardware - the training on a mockup and the testing on actual aircraft parts.

IMMERSIVE VIRTUAL REALITY (VR)

The same maintenance training task as used in the previous studies was developed into an immersive VR training program in order to evaluate the effectiveness of immersive VR for maintainer training. In this condition, participants donned a head mounted display (HMD) and used a 3D mouse to interface with the virtual environment. The only view the participants had was of the images displayed in the visor, giving the participants the impression that they were "inside" the virtual space. Participants in the Immersive condition completed a single pass through the training materials, much like participants in the other training conditions, and then completed the transfer test, identical to participants in the other conditions.

The study was run using dVISE on a Silicon Graphics Reality Monster. A stereoscopic HMD manufactured by Virtual Research was used to present the images to the participants. The HMD consisted of a 640 x 480 display with a refresh rate of 30hz. Ascension magnetic tracking devices were mounted to the HMD and in the 3D mouse to monitor the position of the participant's head and hand in space. This information was used to change the images that were presented on the HMD - any head movements resulted in changes in viewpoint on the HMD, and movements of the hand resulted in movement of the virtual hand on the HMD. Perceivable display lag between the participant's movement and the corresponding update on the HMD was dependent upon the visual complexity of the scene at any given point in time.

Method

Each participant completed the study individually. After the background information was collected from each participant, the participant was given instructions regarding the training procedure. Participants were outfitted with the HMD and 3D mouse and were given a short training session to familiarize them with the immersive system. An extensive series of pilot tests was conducted to optimize the 3D mouse interface to the VR for training purposes. During the training, participants were able to interact with the virtual world by "touching" items in the environment. "Touch" indicated that the virtual hand made contact with the virtual object in the environment. Once the participant touched an object, it turned blue. Only the relevant parts for each step were programmed to change colors. While the item was blue, pressing the button on the mouse allowed the participants to "pick" the item. "Picking" allowed the participants to move objects. When an object was successfully picked, it turned green. To move an item, participants needed pick it and hold the mouse button. The object could be released by releasing the mouse button.

Figure 6. Immersive VR equipment.

To facilitate tool grasping, the appropriate tools were automatically snapped into the participants' hand at the start of a step requiring tool usage. No action was required by the participants to select or grasp the tools. The active portion of the tool was indicated in green. The active portion of the tool needed to make contact with the appropriate component (e.g., bolts, screws, plugs) in order to loosen or tighten the component. When the step was completed, the tool automatically disappeared. As in the other training conditions, training was self-paced and one pass was allowed through the training material. To go from one step to the next, participants needed to press a virtual button. The virtual button was presented as a square, red button that appeared automatically in the field of view when a step was successfully completed. An audio tone sounded in conjunction with the button – the two signaled completion of the step. The virtual button could be pressed in the same manner as objects were picked – the button would turn blue when contact was established, and it would flash green then disappear when the mouse button was pressed. A step could not be repeated once the button appeared in the visual field.

The training program was designed to include automatic changes in camera view to provide the best view for each step. Participants could then move from the pre-set view on their own.

The same audio instructions were presented in the Immersive condition as were presented in all of the other training conditions. Written instructions were not presented within the immersive environment, but trainees could request the audio instructions to be replayed as often as desired.

Immediately following thse immersive training, participants were asked to complete the knowledge test and then to perform the maintenance task on the hardware mockup. As participants performed the maintenance task on the mockup, the same performance measures were recorded as were recorded for the previous studies: performance time and errors.

After the participants completed the transfer task, they were given a questionnaire regarding the immersive VR. This post-study participant questionnaire consisted of open ended question soliciting opinions about what the participants liked and disliked about immersive VR. Suggestions for improvement to the VR training were also requested.

Results

Data from the Immersive condition were compared to results from the Technical Drawing and VE conditions (both passive and interactive versions) and Mockup training conditions. All six sets of data were compared via an analysis of covariance. Significant differences were found in the following main effects: important errors ($F = 7.57$, $p = 0.0007$), test time ($F = 10.38$, $p = 0.0007$), knowledge test scores ($F = 8.69$, $p = 0.0001$), training time ($F = 91.91$, $p = 0.00017$), and a *z*-score for combined performance ($F = 14.12$, $p = 0.0001$). These effects are shown in Figure 7.

Knowledge test scores for the Interactive VE and Mockup training groups were significantly higher than knowledge test scores for the Immersive training condition. There were no differences among the other training groups. Figure 7a shows these results.

Transfer task time, the total amount of time required to complete the training transfer task, was significantly longer in the Passive Technical Drawing condition than the Immersive condition. This effect is shown in Figure 7b. The Mockup condition resulted in significantly shorter test times than both Technical Drawing conditions and Passive VE condition. There is no statistical difference among the Mockup, Interactive VE and Immersive conditions.

Tests of mean differences indicate that the number of important errors committed by participants in the Immersive condition was significantly higher than the number of errors committed by people in both VE conditions and the Mockup condition. This effect is shown in Figure 7c.

Combined performance in the Immersive condition resulted in scores which were significantly lower, and therefore worse, than scores for the Interactive VE

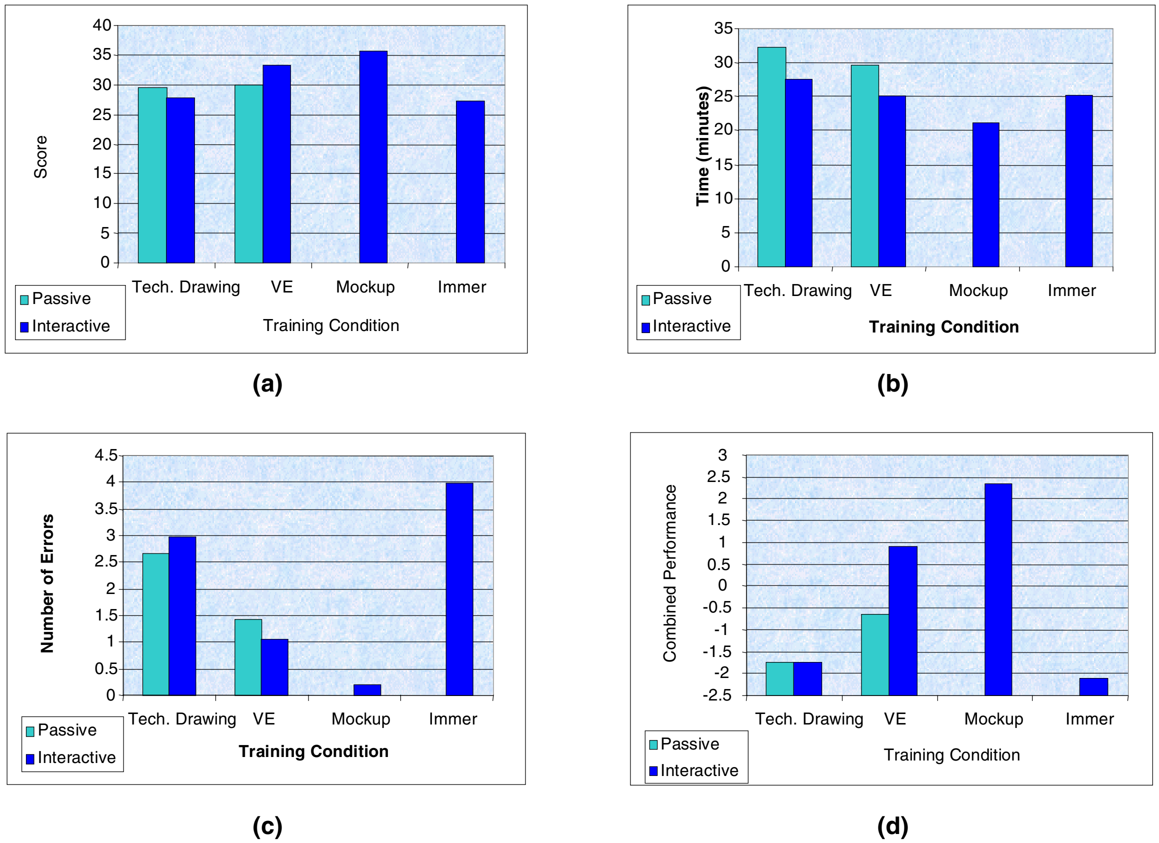

Figure 7. Results of Immersive VR Study.

and Mockup training conditions. Combined scores for the Immersive condition were not significantly different than scores for the two Technical Drawing conditions or the Passive VE condition. These results are shown in Figure 7d.

As shown in Figure 8, mean training time for people in the Immersive condition was significantly different than training times for the other five conditions. It was significantly longer than the training time for the four Technical Drawing and VE conditions, and significantly shorter that that for the Mockup training condition.

Conclusions on Immersive Training

In this study, the use of Immersive VR for training did not improve performance on the transfer task, relative to training in the other conditions. In fact, Immersive training resulted in performance significantly worse than the Mockup and Interactive VE for all but one performance measure. Given this pattern of results, coupled with the increased training time for the Immersive VR over that of the other CBD methods, there is no justification for preferring the current implementation of the Immersive VR-based training over the Interactive VE. Post-study participant questionnaires were examined to determine potential causes for the performance of the Immersive VR training group. A number of interesting findings came out of those surveys.

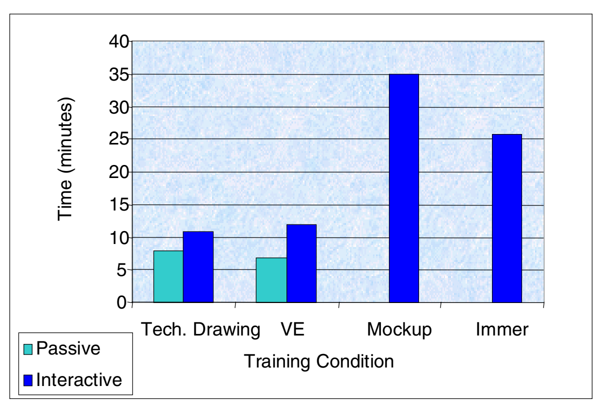

Figure 8. Mean training time.

Nine of the ten participants in the Immersive condition had had no prior experience with immersive systems. This experience was entirely new to them. In fact, most participants responded that completing the Immersive VR training condition was fun and interesting. They enjoyed the chance to experience immersive VR. Second, six out of ten participants responded that the ability to view the task from a number of perspectives and the ability to move freely within the task environment was a distinct advantage for the VR.

Participants also voiced a number of "dislikes" with the VR, and suggested some areas for potential improvement within this training condition. Lack of appropriate depth perception was a concern for five out of 10 participants. In addition, four out of the 10 participants commented that there was a perceived size distortion within the environment, and that some aspect of the interface was awkward to them (e.g. positioning of tools to their hand; selecting each individual fastener). As a result of these unique features of the VR, four of the participants commented that they focused more on interfacing with the VR than with learning the task, in part explaining the poor performance during the assessment portion of the study.

It was observed that, even during the short amount of time people spent using the immersive VR system during training, performance improved. Just as people were beginning to understand how to interface with the system, the training was complete. It is possible that, with more exposure to immersive VR environments, the participants would gain proficiency with the interface, and would be better able to focus on the training task.

VE FOR MAINTENANCE REHEARSAL

This study was a follow-on to the initial training study. In the current study, the effectiveness of VE as a method for maintenance rehearsal was examined. For our purposes, "rehearsal" is defined as completing a brief overview of a task, a significant amount of time after initial task training occurred.

Participants from the original training study were brought back to complete a rehearsal session on the same task on which they were first trained three months before. At the time of the first study, participants were not informed that they would be called back to perform additional tests. In the maintenance rehearsal study, three rehearsal conditions were employed. Participants completed their assigned rehearsal condition, and then performed the same transfer task on a hardware mockup. Task time and errors were recorded.

Rehearsal Conditions

Three rehearsal conditions were compared in this study: two CBD conditions -- Passive Technical Drawing and Interactive VE, -- and no rehearsal. The Interactive VE condition was identical to the material used in the previous training study – the audio instructions, interactive animation, and visual effects were all identical. The Technical Drawing condition was designed to mimic more closely the IETMs used by maintainers currently. This rehearsal condition was developed by taking the Passive Technical Drawing Training condition from the initial training study and removing the audio instructions and the color highlighting. In the "no rehearsal" condition, participants were asked to perform the maintenance task from memory without being refreshed on the task procedure.

Participants were given instructions specific to their study treatment and completed the appropriate task rehearsal. Participants were allowed one self-paced pass through the materials. The amount of time each participant spent completing the task rehearsal was recorded. Immediately following the rehearsal, participants were asked to complete the maintenance task on the hardware mockup.

Test

As participants performed the maintenance task on the mockup, the same performance measures were recorded as were recorded for the training study: performance time and errors. The performance time measure was the time required by the participant to complete the training transfer task.

Participants

Twenty seven participants from the original training study were selected to participate in the rehearsal study. Nine participants from each of the previous training groups (Technical Drawing, VE, and Mockup) were selected and separated into three skill groups (high, medium, and low) based on their performance on the maintenance task during the training study. Measures of previous related experience and spatial aptitude were recorded during the initial training study and were used again in this maintenance rehearsal study. Each participant was assigned to one of the three rehearsal groups based on their previous training condition and skill level. This assignment balanced the type of training and prior performance across all three rehearsal conditions.

Data analysis

As with the training study, task completion times, total errors, and important errors were analyzed using participants' previous experience and skill as covariates. The Interactive VE condition resulted in significantly fewer total errors than the no rehearsal condition ($F = 5.27$, $p = 0.0135$), as shown in Figure 9. No other significant differences in performance were found among the rehearsal groups.

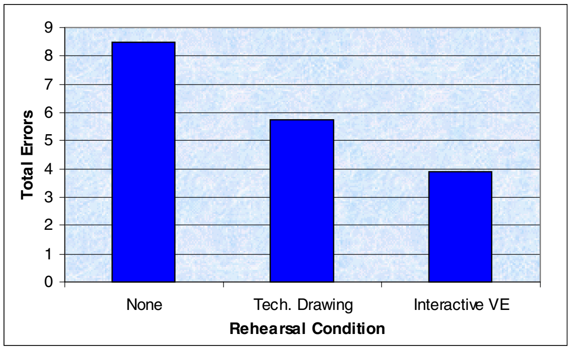

Figure 9. Total errors were lower in the Interactive VE group.

Conclusions - VE for Maintenance Rehearsal

Participants in the Interactive VE rehearsal group had significantly fewer total errors as compared to the participants who had no rehearsal and performed the maintenance task from memory. This finding is not unexpected, considering the number of steps in the task which can be performed in a seemingly arbitrary order. However, no significant differences were found in the number of important errors made among the rehearsal groups. Thus, the participants in all rehearsal groups were able to perform the critical aspects of the task with equivalent accuracy.

What is noteworthy, however, is the fact that participants who rehearsed with the Technical Drawings did NOT have significantly fewer total errors than the participants who had no rehearsal, while the Interactive VE group did have significantly fewer total errors than the no rehearsal group. This finding is similar to the results of the initial training study. However, it us unclear whether the added benefit of the Interactive VE was a result of the level of detail provided in the VE, or if the interactive nature of that rehearsal condition provided the benefit.

CONCLUSIONS

This series of studies systematically evaluated several different aspects of VE-based training for aircraft maintainers. Results of the studies indicate that VE shows significant promise in providing effective training and task rehearsal for a basic maintenance task. However, the VR training is not without problems and difficulties that must be addressed.

Of the training conditions considered in this series of studies, traditional hardware mockup training resulted in the best performance on the maintenance task tested. The fact that the hands-on hardware training resulted in better performance is to be expected. However, the Interactive VE condition resulted in performance did not differ significantly from that of the Mockup training. Results of the studies indicate that VEs show significant promise as an effective, low-cost alternative to hardware mockups for both maintenance training and rehearsal.

Given the current implementation, immersive VR did not provide effective training on the maintenance task. A number of possible explanations for these results were discussed. Immersive VR as a potential training tool needs to be re-evaluated pending advances in immersive technologies.

Collectively, these studies demonstrate that VE holds significant potential for replacing hardware maintenance trainers for some portion of maintenance training. It is unlikely, however, that it will replace hardware trainers completely - at least in the near future. Given the current state of technology, a blend of VE-based and hardware maintenance trainers is a promising solution for instruction in the classroom and rehearsal on the job site. How best to implement both types of training, and under which conditions, must still be determined.

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