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**A PRELIMINARY EMPIRICAL EVALUATION OF
VIRTUAL REALITY AS A TRAINING TOOL
FOR VISUAL-SPATIAL TASKS**

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PREFACE

The mission of the Intelligent Training Branch, Technical Training Research Division, Human Resources Directorate, Armstrong Laboratory (AL/HRTI) is to design, develop, and evaluate the application of artificial intelligence (AI) technologies to computer-assisted training systems. The current effort was undertaken as part of HRTI's research on intelligent tutoring systems (ITS) and ITS development tools. It was accomplished under work unit ILIR 2018, Virtual Interactive Systems for Training and Testing. This research was supported by the Air Force Office of Scientific Research.

We would particularly like to thank Genevieve Haddad, Helmut Hellwig, and John Tangney. We gratefully acknowledge the assistance of Valerie Shute for her timely and insightful reviews, comments, and suggestions.

A PRELIMINARY EMPIRICAL EVALUATION OF VIRTUAL REALITY AS A TRAINING TOOL FOR VISUAL-SPATIAL TASKS

INTRODUCTION

Virtual Reality (VR) has excited the instructional technology community for a variety of reasons. Among these is the notion that instructional systems using VR interfaces are potentially more motivating than traditional 2D interfaces. If learning can be made more interesting and fun, students may remain engaged for longer periods of time. In addition to the potential for longer engagement times, there may be unique benefits to having students *experientially* engaged in the learning context. The VR interface allows learning to be situated in a virtual simulation of the desired transfer context, possibly attenuating the problem of inert knowledge (Whitehead, 1929). Inert knowledge is knowledge that learners fail to apply outside the classroom, even though it is relevant. Another reason for excitement is that the highly visual character of even current-generation VR may be able to capitalize on the disproportionately visual capabilities of the human brain. Finally, VR systems may one day prove to be extremely cost-effective interfaces for simulation-based training, since one VR system can simulate many target systems. Before the potential of VR for instruction can be realized, however, a significant amount of research must be done.

The purpose of this report is to describe our initial attempt at empirically exploring the instructional potential of VR as an interface for simulation-based training, and to describe our agenda for subsequent research. Two characteristics of VR which suggest promise for such training are: (1) The VR interface preserves the visual-spatial characteristics of the simulated world; and (2) the VR interface preserves the linkage between motor actions of the student and resulting effects in the simulated world.

In a VR, if you wish to see what is to the left of a given object, you turn your head to the left. If you wish to activate a switch in a simulated control console, you reach out and "touch" the switch. It is generally assumed that this visual-spatial and motor-response fidelity will enhance both performance in the instructional environment (the VR) and transfer of skill to the operational environment (Kreuger, 1991; Rheingold, 1991). Both parts of this assumption lack a direct empirical basis. Prior to our investigation, we know of no empirical studies documenting training performance in a VR. This report presents training performance data for 31 subjects in two VR environments and discusses implications for future research, especially transfer-of-training research.

The most striking feature of current-generation VR is the remarkable illusion of being physically present in a simulated visual-spatial environment (Held & Durlach, 1991). Although today's systems have relatively impoverished capabilities to convey the rich visual detail of the physical world, the illusion is nevertheless compelling. Our subjects have reported that it is possible to interact with this illusory world as if it were an actual environment with spatial extent. If these

subjective reports are accurate, then it should be possible to capitalize on this aspect of VR for training tasks involving spatial cognition.

Small-Scale and Large-Scale Space

Studies of spatial cognition have shown that it is useful to distinguish between small-scale and large-scale space (Siegel, 1981). Small-scale space can be viewed from a single vantage point at a single point in time. Large-scale space extends beyond the immediate vantage point of the viewer, and must be experienced across time. Subjects can construct functional representations of large-scale space from sequential, isolated views of small-scale space presented in 2D media such as film (Hochberg, 1986) or computer graphics (Regian, 1986). VR, however, offers the possibility of presenting both small-scale and large-scale spatial information in a 3D format that eliminates the need for students to translate the representation from 2D to 3D. The resulting reduction in cognitive load may benefit training (see Salomon, 1979 for a discussion of media symbol systems and learning). In our experiment, we investigate the use of VR to teach procedural tasks requiring performance of motor sequences within small-scale space, and to teach navigational tasks requiring configurational knowledge of large-scale space.

Procedural Tasks

Procedural tasks (e.g., Holmes, 1991) require learning of a series of steps, often contextualized in a small-scale spatial environment. Procedural memory is often distinguished from declarative memory (Anderson, 1982), and accounts for how skills are acquired and retained. Procedural memory is probably a capacity of subcortical brain areas, and is evolutionally old (Tulving, 1983). It develops in human and monkey babies before factual memory (Mishkin, 1982). Because practice is so important to procedural skill acquisition (Anderson, 1982), it has been suggested that VR may be an excellent interface for training procedural skills (Kreuger, 1991).

Modern interactive systems, such as control consoles in industrial plants or weapon systems, have increased the need for human operators to learn procedures. In certain settings, the sequence is learned by rote memorization, as a relatively meaningless sequence. In other settings, the operators know the functionality of the equipment and learn the steps as a meaningful sequence of functional operations. There are potential costs and benefits associated with the decision to teach procedures either as rote or meaningful sequences.

Meaningfulness and Learning

Meaningful organization has repeatedly been shown to be a very powerful antecedent of learning. The effect has been shown across diverse paradigms

involving chunking in short-term memory (Bower, 1972; Kanigel, 1981), elaborative rehearsal in short-term memory, and subsequent retrieval from long-term memory (Craik & Lockhart, 1972; Chase & Ericsson, 1981), and the superiority of gist over verbatim recall of sentences (Bransford & Franks, 1971). Even memory for simple procedures and common events has been shown to benefit from organizational cues (Bransford & Johnson, 1973). It is generally true that verbal skills taught in a meaningful way are acquired and retained better than when they are taught in a rote fashion.

In contrast, the effect of meaningfulness has not yet been clearly established for procedural tasks. Empirical research is sparse for the effect of meaningfulness on procedural learning, and the available evidence raises more questions than it answers. For example, Singer, Korienek, and Ridsdale (1980) compared learning strategies for a procedural task that required subjects to learn a sequence of button and lever responses. Both acquisition and transfer performance indicated that a rote strategy was as good as a chunking strategy, in which subjects grouped responses into sequences of three responses. An imagery strategy was also tested. This strategy directed subjects to visualize each button or lever in a warehouse storage bin. In comparison with rote learning, imagery yielded worse acquisition performance and comparable transfer performance. On one hand, the chunking and imagery strategies may not have meaningfully organized the learned sequencing. Accordingly, the imposition of other meaningful organizations might facilitate procedural learning (Ho & Shea, 1979; Wright, 1991). On the other hand, the intrinsic spatial-temporal relationships might be the most meaningful organizer of procedural tasks. We know, for instance, that the method of loci is a powerful learning strategy (Bower, 1972). In this strategy, subjects associate responses with imaged spatial locations. In many procedural tasks, including the one studied by Singer et al., responses are inherently associated with spatial locations. Consequently, the imposition of other organizers might be superfluous.

In this study, we investigated both rote and meaningful encoding strategies and their impact on the acquisition of procedures in a VR.

Navigational Tasks

Navigational tasks require individuals to learn and then navigate through a large-scale spatial environment. The most generally useful form of spatial knowledge for navigation is configurational knowledge. "Configurational" means that the cognitive representation preserves the spatial relationships in a spatial array, including distances among objects and relative placement of objects. Regian (1986) showed that subjects can develop a mental model of large-scale two-dimensional (2D) space that preserves configurational aspects of the space in the manner of a map. Performance on tasks which access configurational knowledge learned from computer-simulated environments was shown to be highly correlated with performance on analogous tasks which required configurational knowledge about real-world environments.

Subjects are able to internalize configurational, functionally map-like representations of environments and then perform tasks which require access to that representation. Evidence suggests that subjects are able to create suitable spatial representations under various stimulus conditions. Subjects are able to extract spatial information from graphical, 2D spatial arrays (Regian, 1986; Stasz, 1979) as well as from verbally described spatial arrays (Glushko & Cooper, 1978; Regian, 1986). The current research will make a preliminary evaluation of VR as an instructional interface for teaching three-dimensional (3D) spatial knowledge. Subjects will be trained in two 3D virtual worlds (one small-scale and one large-scale) and then asked to perform tasks requiring access to the resulting cognitive representation. In the case of the small-scale space, a procedural task will be performed. In the case of the large-scale space, a navigational task will be performed.

METHOD

Subjects

Thirty-one subjects provided by a local temporary employee service were each paid for 20 h of participation. Subjects ranged from 18 to 35 years of age. One-half of the subjects were male. All were high school graduates.

Stimuli

Two VR worlds were created for the experiment. One of the worlds, the virtual console, was a representation of small-scale space. The other world, the virtual maze, was a representation of large-scale space. These two virtual worlds were designed to support analogs of distinctly different tasks. The first was a procedural console operations task and the second was a 3D maze navigation task. Figure 1 illustrates the virtual console used in the procedural console operations task.

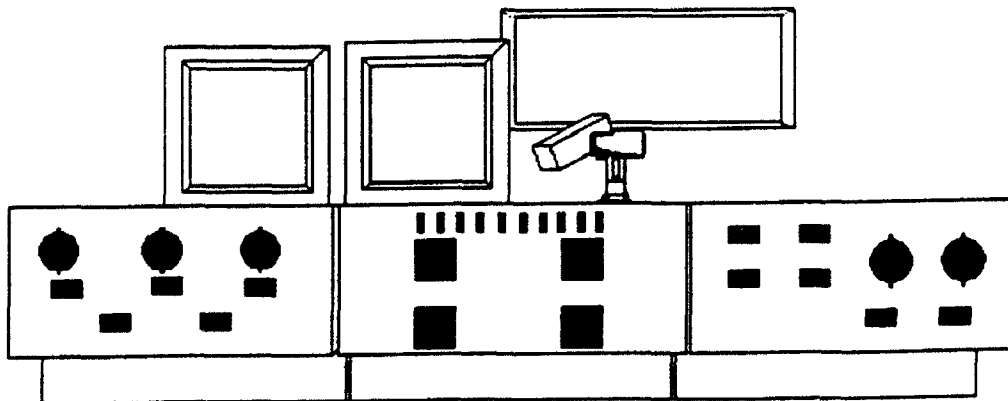


Figure 1
Black-and-white representation of the virtual console used for procedural training in a small-scale virtual environment

The virtual console was broken up into three rectangular panels arranged along a single vertical plane. The panel on the far left consisted of three knobs and five buttons. The "size" of the buttons could be considered to be the same "size" as the cross section of the index finger on the subject's virtual hand. The center panel consisted of four buttons and a countdown timer. The panel on the far right consisted of two knobs and six buttons. Each button and knob turned yellow when activated in the proper sequence. The console procedure was strictly sequential. During the training phase of the console operations task, a green training prompt appeared behind the next button or knob in the sequence. None of the buttons or knobs could be activated out of turn. In the testing phase of the console task, the green training prompt was removed, but the yellow feedback prompt was retained.

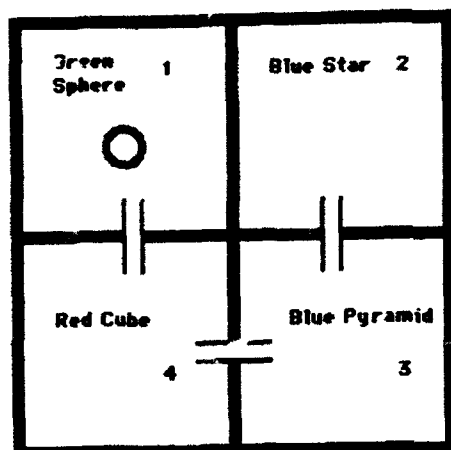
The virtual maze was a twelve-room structure consisting of three levels (floors), four rooms to a level. Each room was cubical in shape and contained a unique color-coded object to identify the room. There were four different types of objects: star, cube, sphere, and pyramid. Each object could be one of three colors: red, green, or blue. Tunnel-like hallways connected some adjacent rooms. Rooms had from one to three hallways adjoining them. Every room was connected to at least one hallway. All walls and hallways were made impermeable. Figure 2 shows the layout for the 3D virtual maze.

In the virtual maze, there were four north-south hallways, four east-west hallways, and three up-down hallways. The maze was constructed with the following constraints. All rooms had at least one connecting hallway, thus allowing access to all of the rooms. Four rooms had only one connecting hallway, six rooms had two connecting hallways, and two rooms had three connecting hallways. The rooms and halls were uniformly colored. The walls of individual rooms were red, the floors and ceilings gray, and the hallways yellow. Figure 3 approximates how the maze appeared to the user. In this depiction, the user is standing on the first floor in the blue pyramid room, looking north toward the blue star room.

Equipment

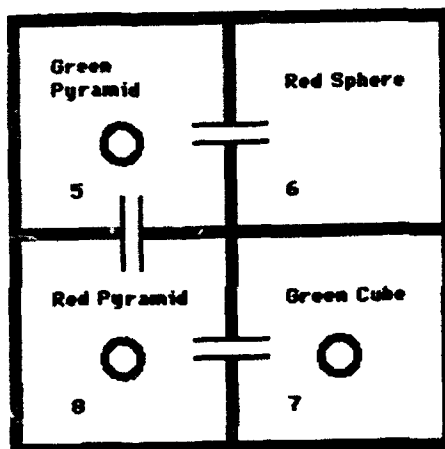
Experimental apparatus included a Silicon Graphics IRIS 4D 210/VGX, a Silicon Graphics IRIS 4D 310/VGX, and an Apple Macintosh IIx. Proprietary hardware and software supplied by VPL Research Inc. consisted of VPL Model 2 Eyephones, the eyephone control unit, standard VPL data gloves, data glove control unit, VID/IO video signal splitters, and POLHEMUS 3-Space tracking devices. The software used to create the static virtual worlds was RB2 Swivel. The software that controlled the virtual reality was VPL's Body Electric and the real time rendering software used on the Silicon Graphics workstations was VPL's Isaac.

The Macintosh acted as a front end for the system which allowed the two workstations to perform all of the intensive graphics generation. The Macintosh continually received position and attitude information from the tracking devices and data glove and used this data to compute what the user should see. This information was then sent to the Silicon Graphics workstations via ethernet and the appropriate graphics image was generated and then displayed in the user's eyephones.

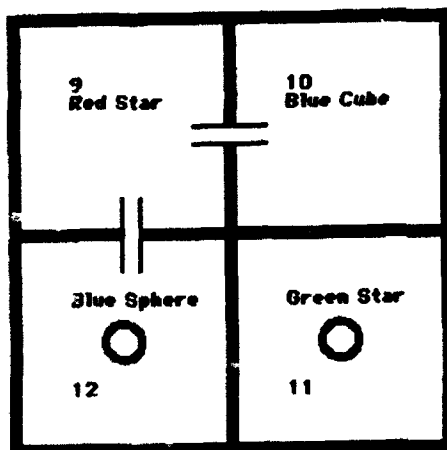


First Floor

* The circles denote passages between floors



Second Floor



Third Floor

Figure 2

Two-dimensional representation of the virtual maze used for training in a large-scale three-dimensional virtual environment. The small parallel lines represent hallways, and the circles represent passages between floors.

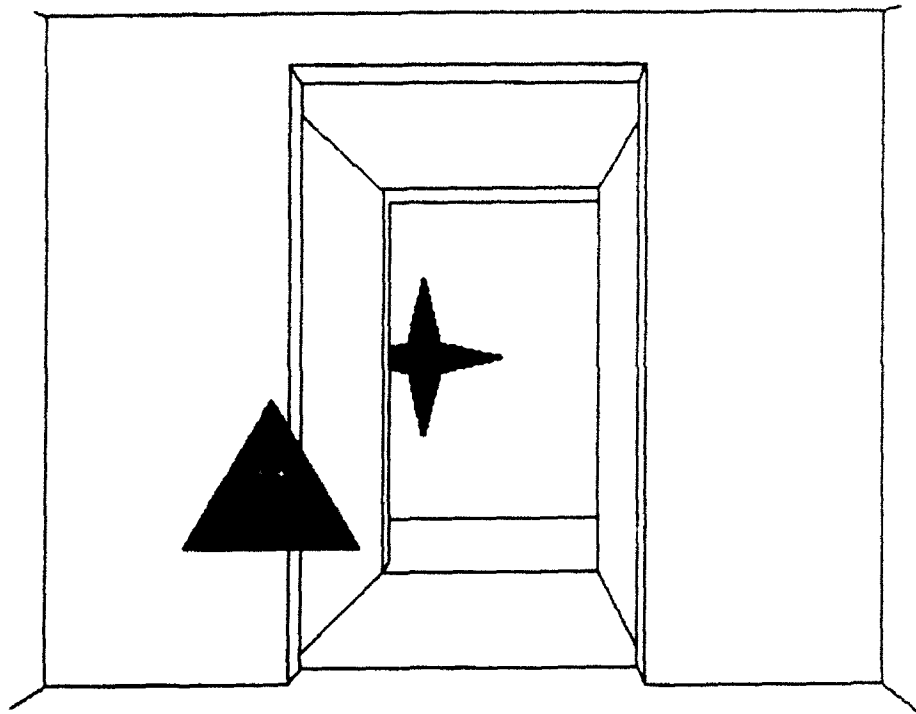


Figure 3
Black-and-white rendering of the maze from a user's vantage point.
The user is standing on the first floor in the blue pyramid room,
looking north toward the blue star room.

Procedure

Thirty-one subjects learned and performed two VR tasks. The first task was a procedural console operations task requiring performance of a motor sequence within a small-scale space (the virtual console). The second task was a navigational task requiring 3D configurational knowledge of large-scale space (the virtual maze). Each task involved a training phase and a testing phase.

Console Operations

For the console operations training phase, subjects were randomly assigned to one of two groups, both of which were taught a complex seventeen-step procedure. Both groups saw visual prompts (green highlighting of the button or knob) in the VR indicating which button or knob to activate next. One group was given meaningful verbal prompts about what each of the button or knob operations accomplished. For example, they were told that the first button turned on the console; the second button activated the missile platform, etc. They were

thus provided with a meaningful task description. The other group was given no explanation for the operation and was simply told which button or knob operation to perform next.

For both groups, the green visual training prompt was used during the training phase. In addition, each subject was instructed by the proctor on how to successfully push buttons and turn knobs using a data glove. Subjects were led through the procedure by the proctor (either with meaningful or rote verbal prompts) until they could perform the procedure with no verbal prompts. The time to reach this stage of training performance (successful performance of the procedure with visual prompting but no verbal prompting) was noted. The subject was then allowed to perform several more proficiency confirmation trials before moving on to the testing phase.

The console operations testing phase was the same for both groups. Three minutes were given to each subject to accomplish the same procedure that was taught during training. Subjects performed the procedure five times during the testing phase, each with a 3-min time limit. There was a 2-min rest period between performances. No help was given in the form of the visual prompting, verbal prompting, or any other proctor assistance.

Maze Navigation

The training phase of the virtual maze task involved moving around in the maze, first under guided conditions and then under free exploration conditions. Each subject was first given three different guided tours of the maze. The three tours were identical across subjects. The tours were guided by way of verbal commands given by the test administrator. For example, one instruction was: "You are now in the blue pyramid room facing north. Turn to the west and proceed into the next room." Upon the completion of these tours, all rooms and hallways in the maze had been visited at least one time. Each tour had different initial and final rooms. Finally, subjects were told they would soon be tested on their knowledge of the maze and were given an hour to explore and become familiar with the layout of the maze.

The testing phase of the virtual maze task included three different tour assignments. Each tour had specific starting and goal rooms. The testing tours were not the same as the training tours. The three tours taken together were designed to force the subject to visit all of the rooms in the maze at least one time. The tours could be optimally completed by visiting 8 rooms (3-4-1-5-8-12-9-10), 4 rooms (11-7-8-12), and 6 rooms (2-3-4-1-5-6), respectively. Subjects were told that their goal was to get from the starting room to the goal room while minimizing intervening rooms visited. A perfectly performing subject would visit exactly 18 rooms in completing the three tours.

RESULTS

Console Operations

Subjects were able to learn the console procedure under both instructional conditions, as evidenced by their subsequent ability to perform the procedure without prompts. All 31 subjects accurately completed all 5 tests in under 3 min. Thus, test accuracy was perfect for all subjects. There was no effect of instructional meaningfulness on latency to acquire the console procedure. Subjects given meaningful instructions learned to perform the procedure without verbal prompts in an average of 19 min ($SD = 12.9$) as compared to an average of 17 min ($SD = 10.4$) for subjects given rote instructions ($t(29) = 0.57$, $p = 0.58$). There was also no effect of meaningful instructions on the accuracy or speed of performing the procedure without prompts during the testing phase. Table 1 shows average latencies (in minutes) for performing the procedure on the five test occasions, broken out by instructional group. There was a practice effect on latency ($F(4,116) = 24.12$, $p < .001$), no effect of instructional meaningfulness ($F(1,29) = 0.85$, $p = 0.36$), and no interaction ($F(4,116) = 0.93$, $p = 0.45$).

Table 1. Average Latencies for the Procedure Tests (in minutes)

Instruction Type	Test 1	Test 2	Test 3	Test 4	Test 5
Meaningful (n=15)					
Avg.	2.02	1.69	1.52	1.18	0.65
SD	(.94)	(.99)	(.87)	(.80)	(.74)
Rote (n=16)					
Avg.	2.08	1.77	1.85	1.52	1.09
SD	(.71)	(.63)	(.71)	(.64)	(.71)

Maze Navigation

Subjects were able to learn the virtual maze, as evidenced by their ability to navigate within the maze after training. The dependent measure for the maze navigation task was the number of rooms traversed in the test tours. The mean number of rooms traversed was 10.1, 4.8, and 6.7 for tests 1, 2, and 3 respectively. Summing across the three tours, subjects entered an average of 21.7 rooms in completing the tours. Perfect performance on completing the three tours would have involved entering 18 rooms. Random performance distributions were estimated by a Monte Carlo analysis (described in the next section) and yielded

expected values (means) of 83, 21, and 37 rooms visited. These data are summarized in Table 2.

Table 2. Summary of Maze Navigation Test Tour Results

# Rooms Entered		Tour 1	Tour 2	Tour 3	Total
Fewest Possible		8	4	6	18
Observed Avg.	(n=31)	10.1	4.8	6.7	21.7
SD		(2.5)	(2.2)	(1.3)	
Expected Value					
Assuming Random Performance		83	21	37	141

Monte Carlo Maze Analysis

The statistical properties of the maze were explored using an iterative random walk approach. A computer program was written that represented the maze. This program would ask for the initial room, final room, and number of iterations to be performed for some tour and would proceed to "walk through" the maze in a random fashion starting at the initial room until the final room was found. The program would repeat this procedure for the specified number of iterations. Iterations of length 10,000 were used for all tests. Information about each iteration was saved, including length and frequency of each tour. From this information, the program generated probability distributions and determined the number of rooms needed to satisfy a $p < 0.05$ criterion. This criterion was derived by computing the probability of the minimum length tour, and adding it to the probability of each tour of successively greater length until the total probability exceeded the criterion. For example, the minimum number of rooms for Test 1 was 8. The probability of completing the tour in this number of rooms by chance in a random walk was 0.0026 (26/10,000). The probability of completing the tour in 10 rooms by chance was 0.0076; the probability of completing the tour in 12 rooms by chance was 0.0126; and the probability of completing the tour in 14 rooms by chance was 0.0161. The sum of these probabilities is 0.0389. That is, the probability of completing the tour in 14 rooms¹ or less by chance is less than 0.05. Thus 14 rooms is the ($p < .05$) criterion for Test 1. The probability of completing the tour in 16 rooms by chance is 0.0153. Adding

¹ The tour could only be completed by entering even numbers of rooms.

this probability brings the total probability over the criterion so that 16 rooms fails the $p < 0.05$ criterion.

When a subject completed Test 1 in 14 or less rooms, we concluded that performance reflected learning as opposed to being determined by random decisions. The probability of that conclusion being in error was less than 5 in 100. According to this criterion, 29 of the 31 subjects manifested learning on Test 1. Fifteen of those subjects completed the test in the minimum number of moves. Performance was even better on Test 3. All 31 subjects exhibited learning according to the .05 criterion, and 23 of them completed the test in the minimum number of rooms. The importance of these tests is accentuated when they are compared to Test 2. For Test 2 we were unable to establish a .05 criterion because the probability of doing the optimal tour by chance was one in four² (.25). Although 23 of the 31 subjects did Test 2 in the minimum number of rooms, we cannot rule out chance performance as confidently on the basis of this test alone. In contrast, Tests 1 and 3 provide clear evidence that subjects learned configurational information in the virtual maze.

DISCUSSION

Subjects learned spatial-procedural and spatial-navigational skills in a VR. The console data show that subjects not only learned the procedure, but continued to acquire skill while being tested on the procedure, as the tests provided continued practice in executing the procedure. One interpretation of the lack of any instructional meaningfulness effect on learning or performance might be that encoding specificity effects (Baddeley, 1982) are overcoming the usual advantage of meaningful instructions. The excellent performance of rote learners may have been due to the context dependent nature of procedural learning and to the availability of appropriate retrieval cues at test time. If this explanation is correct, test performance should fall when similarity is reduced between cues in training and testing environments. This performance should improve when meaningful instructions are given. We are now making preparations to test this prediction directly. We have developed a 2D single screen console procedure trainer analogous to the VR trainer. We plan to train and test the procedure in both environments. We are also building a mockup of the console to test the hypothesis that encoding specificity is greater not only in VR-to-VR transfer but also in VR-to-physical transfer.

The maze data show that subjects learned 3D configurational knowledge of the virtual maze and were able to use the knowledge to navigate accurately within the VR. The argument that this is configurational knowledge rather than route knowledge is bolstered by the fact that training and testing routes were

²Because the tour was so short, even if the subject randomly picked an exit from each succeeding room the probability of stumbling on the goal room was high.

different. Two issues are opened by this finding. First, is there any advantage for learning from the VR representation as compared to learning from a 2D "God's eye view" representation of the same maze? We have created such a representation, similar to the computer-based representations used by Regian (1986), Stasz (1979), and others. Each room is represented by a constant-sized square that is centered in the middle of a computer screen. Within each room, there is a drawing of the appropriate object for that room (i.e., green star, blue pyramid, etc.). Each room also has hallway or passage icons placed in their correct positions. When subjects use this environment, they can only see the room that they are "in." To move between rooms, the subject uses the mouse to click on a hallway or passage icon, which brings up a display of the new room. Twenty subjects have completed the 2D analog of the maze task. The same training and testing procedure is being used as in the VR version of the task, with identical training tours and testing tours. Learning under this condition appears to be less engaging than learning from the VR condition, as subjects frequently complain that the 1-h free exploration is too long. Not surprisingly, test performance is less accurate than learning from the VR condition (so far, mean tour lengths are 18, 11, and 8 for Tests 1, 2, and 3, respectively). There is also significantly more variability in test performance than was found after VR-based learning.

The second issue opened by the maze data is the issue of transfer-of-training from the VR navigation real-world navigation. Given the correlation between computer and real-world navigation tasks reported by Regian (1986), it seems possible that such transfer will occur. We are working towards testing this prediction by building a VR representation of an actual building. Our plans are to train subjects on configurational knowledge of the building using a VR approach and a 2D approach, and then directly assess the subjects' abilities to navigate through the building.

In the introduction to this paper, we described two characteristics of VR which suggest promise for simulation-based training. They were: (1) The VR interface preserves the visual-spatial characteristics of the simulated world. (2) The VR interface preserves the linkage between motor actions of the student and resulting effects in the simulated world. These two characteristics define a kind of fidelity that is possible with VR interfaces that are to be used for training. As we pursue the potential for this technology for training, we intend to focus on the fidelity issue. It is not necessarily true that higher fidelity simulation always leads to better training.

In the context of flight simulator-based pilot training, Lintern and his colleagues have shown that in some cases, added fidelity has no effect on skill transfer. In other cases, reducing fidelity according to specific principles (augmented feedback) actually aids in training (Lintern, Roscoe, Koonce, & Segal, 1990; Lintern, Roscoe, & Sivier, 1990). Many part-task training regimes reduce fidelity early in training in order to reduce complexity (Regian & Schneider, 1990). It should not be assumed that increased fidelity will lead to increased skill transfer. Given computational and economic limitations on VR, it will be important to make empirically guided decisions about where VR has application for training, which

dimensions of reality need to be simulated to accomplish transfer, and what level of detail is required. The present experiments are steps toward an empirical foundation for those decisions.

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