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Navigation Training in Virtual Environments

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ABSTRACT

Virtual environments (VE) promise important opportunities as future interfaces to computational systems, especially where such technology can take advantage of strong human visuospatial capabilities. Although such synthetic environments often project homeomorphic physical representations of real-world layouts, it is not known how individuals develop representational models to match these environments. To evaluate this process, this experiment examined participant's accuracy in reproducing triadic representations of objects, having learned them previously under 1 of 3 different conditions. The layout consisted of 9 common objects arranged on a flat plane. These objects could be viewed in a free VE, a static VE, or from the static view of a map. The first condition allowed active exploration of the environment while the latter two conditions allowed the participant only a passive opportunity to observe from a single viewpoint. Viewing conditions were a between-subject variable with seven participants randomly assigned to each condition. Performance was assessed by the response latency to judge the layout accuracy of three object triads from different rotated positions. Results showed a linear increase in response latency as the rotation angle increased in both the map and static VE conditions. In contrast, and like findings from real-world investigations, the virtual navigation condition did not show such an effect for orientation angle. These results suggest that the spatial knowledge acquisition from navigation in VEs can be similar to actual navigation when the viewing condition is unconstrained. One caveat being that, while performance was more robust once knowledge of the spatial layout was acquired, participants took significantly longer to learn the layout in the virtual navigation condition as compared with either the static VE or the map conditions. Given that such differentiated learning effects are due largely to limits to contemporary VE technology, our study confirms that VEs hold great promise for spatial navigational learning.

1. INTRODUCTION

Learning how to complete a complex task is often made even more difficult by the additional burden of needing to know about the spatial layout of the environment in which it is performed. Many tasks can be taught effectively only in highly specific conditions as in, for ex-

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Requests for reprints should be sent to P.A. Hancock, Department of Psychology, University of Central Florida, P.O. Box 16139, 4000 Central Florida Boulevard, Orlando, FL 32816. E-mail: phancock@pegasus.cc.ucf.edu ample, learning to fly an airplane with a particular configuration of controls. Other types of tasks, such as navigating around a damaged nuclear power plant to neutralize dangerous radioactive material, not only must be carried out in a specific context, but also requires the operator or agent to assimilate detailed knowledge of the spatial layout in which events are anticipated to occur. If the actual setting or location where the real task will take place is available for training, performance transfer is close to optimal. However, if the actual task setting is not available, then training generally consists of two integrated components: training for the specific task actions required and the acquisition of the spatial knowledge (or layout knowledge) necessary to reach the task site.

There are many tasks that require spatial knowledge for which the actual environment is not immediately available for training. Often training cannot be carried out in the real-world environment due to safety hazards or expense. If safety is not an issue, the sheer size of the environment needed frequently makes a real-world training program impractical. To counteract the problem of environmental size in training, we often use maps to foster navigational capability. Maps are available in a variety of forms and are suitable for spatial learning under many circumstances; however, they generally convey one-dimensional, configurational information. Physical models of real-world environments are sometimes substituted for the real-world locations, but these surrogates are often unwieldy in size, expensive to build, store, and not easily modified. An emerging tool for navigational training is the VE. VEs offer trainees many of the benefits gained from maps and scaled models, while providing additional advantages, such as the opportunity to learn in an environment that is perceptually comparable to the real world.

2. DISTORTIONS OF INTERNAL SPATIAL REPRESENTATIONS

An alignment effect is an influence on an internal spatial representation in which judgments and navigation are more accurate and efficient when oriented to a specific direction. Alignment effects can have deleterious effects on navigation and may result in a loss of orientation, or becoming “lost.” Alignment effects have been shown to occur as a result of studying maps that have been oriented at an angle inconsistent with the environment as it is then visibly perceived (May, Peruch, & Savoyant, 1995; see also Peruch & Lapin, 1993) and after exploring a physical space while continuously oriented in a single direction (Presson, DeLange, & Hazelrigg, 1987). May et al. also demonstrated that map study and one-directional navigation also lead to alignment effects in spatial representations gained from virtual as well as real environments. In essence, learning from a specific orientation biases the individual toward that orientation, and while advantageous from one viewpoint, this differentiated learning is disadvantageous as soon as that particular viewpoint is abandoned.

2.1. Alignment Effects From Maps

Due, in part, to their ubiquity, maps are frequently used to convey spatial layout information because they often already exist. Maps can be easily created and modified, are inexpensive, convenient, and simple to use, and do not require extensive storage space. Maps are available in many forms. Two types that are commonly used during navigation are north-up and track-up. It should be recognized that orientation in maps has been of concern and the subject of enquiry since the origins of cartography itself when early maps were oriented east-up (Jancey, 1994). While track-up maps may appear to be more recently developed, they were actually developed early in the mapping process (Ogilby, 1675, as cited in Moreland, C., & Bannister, D., 1983). A north-up representation, for example, a present-day road map, is generally read from a single orientation. The mental representation gained from a north-up map is, thus, often orientation specific, and the judgments made with this form of representation are influenced by the unique viewpoint from which the map itself was learned. Using these maps, navigation becomes more effortful and time consuming when one's orientation to the world becomes increasingly disparate to the orientation of the map. Track-up maps are dynamic, ego-centered displays that revolve around the navigator's current position so that the orientations of the world and map are always the same. Such maps are now being included as navigational aids for advanced transportation systems (Hancock & Parasuraman, 1992). An advantage of a track-up map over a north-up map is that it helps the traveler maintain superior orientation and therefore situation awareness (Endsley, 1995; Smith & Hancock, 1995). Alignment effects are less likely to be present in the internal spatial representations gained from track-up maps because they do not constrain the learner to a single directional view.

Contemporary evidence indicates that spatial knowledge acquired from maps is qualitatively different from that acquired from real-world navigation (Evans & Pezdek, 1980; Kulhavy, Schwartz, & Shaha, 1983; Presson, DeLange, & Hazelrigg, 1989; Presson & Hazelrigg, 1984; Shepard & Hurwitz, 1984; Thorndyke & Hayes-Roth, 1982). Presson and his associates found that learning from maps, which they termed secondary learning, leads to alignment effects, whereas learning from physical exploration, or primary learning, does not (Presson et al., 1989; Presson & Hazelrigg, 1984). In one of their experiments, half of the participants learned from paths that were painted on the floor and the other half learned from a 50- by 50-cm map held vertically. The learning in each condition was visual and always from a single vantage point. Blindfolded participants were then led to several locations by the experimenter in an indirect, meandering walk. The task was to indicate, while still blindfolded, the direction of a particular location specified during the walk. Participants were provided with information concerning which other locations were directly in front or behind them. The results of these experiments showed a significant advantage of learning from a route over learning from a map of that route. Participants were more accurate in estimating the direction to target locations in contra-aligned judgments after viewing a route than a map. In judgments that were aligned to the map orientation, participants were significantly more accurate in the map condition. Presson and Hazelrigg concluded that in the secondary learning condition, participants used an abstract frame of reference and that all judgments were made relative to that frame of reference. Information was relative to the surrounding area, and no additional frame of reference was necessary in the primary learning condition. Other researchers have also found significant alignment effects when asking participants to make judgments that are contra-aligned to a map (e.g., Rossano & Warren, 1989).

Presson et al. (1989) extended their earlier findings by examining different sizes of maps and routes. The method was similar to their earlier study; however, participants were provided with either small-scale or large-scale paths. Participants in the large path condition were told that the path on the floor was a map of the route instead of the route itself. Participants in the small path condition were told that the path on the floor (which was 40 × 40 cm) was a map. The same task of learning a path and then making blindfolded directional judgments was used. The accuracy of these judgments was the primary dependent variable. The result of this manipulation was that the small map condition showed orientation effects as in the earlier studies, but the large map and route conditions failed to show such effects. Subsequent experiments focused on different map sizes and route sizes, varying from 2 to 12 ft for the maps and 2 to 32 ft for the routes. Alignment effects decreased across the map sizes, and aligned judgments were more accurate with the map learning while contra-aligned judgments were more accurate with the route learning. Presson and his colleagues conducted several further experiments that focused on maps of different sizes. In these studies, they again found that small-scale displays were represented in an orientation-specific way, while representations for large-scale displays were free of these alignment effects.

Further evidence that alignment effects exist in cases of map learning but not navigational experience comes from a study by Evans and Pezdek (1980) using the rotation of object triads. Response latency was the dependent variable and participants were asked to indicate whether the spatial relationships between three objects were correctly represented. Object layout was learned via either navigation or studying a map. Response latency increased linearly with rotation angle for participants in the map condition but not the navigation condition. These results suggest that information learned via a map is stored as a single orientation and that individuals must rotate the mental representation back to the orientation in which they learned the information in order to make a correct judgment. This alignment effect was not found for navigational experience, suggesting multiple perspectives or a different cognitive representational structure.

The results reported by Boer (1991) also confirm that mental rotation may be used when alignment effects are present in one's internal representation of the environment (see also Shepard & Cooper, 1983). Participants performed a directional pointing task after imagining that they were facing a specified direction. The condition in which they were told to imagine that they were facing the direction that they were already facing took the least amount of time. Response times increased in a mirror-like fashion in both the positive and negative rotations until about 150 degrees while the response times decreased at 180 degrees. Boer interpreted these results as indicating that participants were performing mental rotation.

2.2. Distortions of Distances From Maps

Thorndyke and Hayes-Roth (1982) compared the representation of a building that people formed from either navigating around the building itself or from memorizing a map. Results in a distance estimation measure showed that the performance of the map learning group exceeded that of the navigation group, but only early in navigational learning. This finding is very similar to the consistent overestimation of spatially far distant points in one of McNamara's experiments (McNamara, 1986). McNamara found that participants overestimated the distance between objects that were in different superordinate categories or rooms, but when objects were placed in the same room, the distance between the objects was consistently underestimated. Thorndyke and Hayes-Roth also observed that navigation participants made more errors when the route contained multiple turns than when the route was simpler as compared to the map learning group. These authors further reported results from a different dependent measure in the same experiment in which participants were required to point to a location from a start point, or point to a location from an imagined start point. The orientation and simulated orientation tasks showed much the same pattern of results as those for distance estimation. Navigation trained individuals showed lower levels of angular error than the map group while the amount of experience lowered the overall level of angular error. The findings reported by Thorndyke and Hayes-Roth and McNamara support the assertion that map learners acquired a bird's-eye view of the environment, while navigational learners appear to have acquired a more flexible representation. One obvious advantage of map learning is the accuracy with which global relationships can be established. However, map learners are very error prone when they are required to change their orientation, whereas navigational learners are not.

2.3. Alignment Effects from Physical Exploration

Findings from several studies support the contention that exposure to multiple viewpoints during spatial learning explains why mental representations resulting from navigation fail to exhibit alignment effects (but see Warren, Rossano, & Wear, 1990). However, during navigation in the physical world, kinesthetic cues associated with physically turning the head and body also accompany the visual stimulation. Therefore, in regard to creating internal representations of real spaces that are free from alignment effects, physical travel has the added benefit of kinesthetic cues not available in maps. Presson, DeLange, and Hazelrigg (1987) found that blindfolded individuals who walked along a path while maintaining a constant orientation made more errors in estimating the direction to prespecified targets than individuals who walked along the path and were allowed to turn to face any orientation. Therefore, kinesthetically experiencing multiple orientations is also an important factor in developing comprehensive internal representations that suppress the acquisition of alignment effects.

2.4. Alignment Effects in Virtual Environments

Map learning is not an ideal method of acquiring spatial knowledge. An alternative, which is comparatively inexpensive, yet potentially as effective as real-world training, is training in VEs. VEs are fairly simple to create, are easily modified once they are created, and require little storage space other than computer memory. The disadvantages seen in map learning may be potentially overcome by training in a VE. Many VEs also provide kinesthetic information, which, as previously noted, is helpful for acquiring accurate spatial representations. Through the use of a head-mounted display that allows control over orientation via head and/or full body movements, a VE is capable of providing multiple correspondent visual and kinesthetic cues. A number of studies have indicated that spatial learning from navigation VEs is similar to spatial learning from a physical environment (Bliss, Tidwell, & Guest, 1997; Peruch, Vercher, & Galltheir, 1995; Waller, Hunt, & Knapp, 1998; Wilson, Foreman, & Tlauka, 1997; Witmer, Bailey, Knerr, & Parsons, 1996). May et al. (1995) demonstrated that alignment effects also occur in VEs. Participants were given maps that were aligned with the environment, contained a 90-degree rotation, or were contra-aligned to the environment. The task of the participant was to move as quickly as possible through the VE. The results showed alignment effects that increased as the degree of misalignment increased. Thus, while VEs provide a viable method for the development of spatial mental representations, specific concern has to be directed as to how such environments are structured and explored if alignment effects are to be obviated.

2.5. Theories of Orientation

The experiments described above support a multiple viewpoint model for object recognition as proposed by Tarr and Pinker (1989). The multiple viewpoint hypothesis suggests that object recognition is accomplished by comparing views of the object that were stored in memory to rotations of the exemplar that was presented to the participant on an individual trial. The multiple views theory suggests that objects are rotated to a learned viewpoint and then the decision is made regarding object recognition. To test this hypothesis, Tarr and Pinker had a group of participants learn three figures in four different orientations (0, +45, +135, and –90 degrees). The experiment consisted of 12 blocks of practice orientations and 1 block of surprise orientations following. Each block consisted of each of the three figures in all four orientations. In addition, each figure was presented eight times in both its standard and reversed orientations. These combinations made 192 trials for each block, in addition there were 14 practice trials at the beginning of each block. The surprise block consisted of the 384 trials the same orientations plus new orientations (–45, +90, –135, and +180). Participants showed learning across the 12 practice blocks as the mean reaction time decreased substantially from block 1 to 12. The result of the surprise block showed that the previously studied orientations were as fast as in the previous block, but that the new orientations were significantly slower than the learned orientations and in fact were as slow as the response times to the learned orientations in block 1. Thus, there was no transfer with increased practice, and participants seemed to encode the figures in the particular orientation in which they had been learned. The results of Tarr and Pinker are in close agreement with the previously discussed experiments of Thorndyke and Hayes-Roth (1982), Evans and Pezdek (1980), and Boer (1991). Each of the previously mentioned authors point to a lack of experience in multiple perspectives as a reason for alignment effects found in map learning. They also point to mental rotation as the difference in the accuracy or response time.

2.6. Summary

The results of these collective experiments on spatial orientation seem to be very clear. Learning a spatial layout via navigation results in an orientation-free representation, and learning a layout from a map results in an orientation-specific type of representation. Participants in map learning conditions were quicker and more accurate in responding to spatial questions when there was no rotation required or when the judgments were aligned with respect to the learning condition. Participants in the navigation conditions exhibited an orientation-free representation in that they were equally fast and accurate making aligned and contra-aligned judgments.

2.7. Objectives of this Research

Given this existing knowledge, the objective of this research was to explicate the characteristics of a display that are antecedent to internal spatial representations that are free from alignment effects. We measured the accuracy of internal spatial representations by the response latency in discriminating between novel and previously viewed sets of object triads, presented at various orientations. Three display conditions were examined: single viewpoint map, single viewpoint VE, and multiple viewpoint VE (i.e., navigation). Alignment effects were expected to demonstrate a linear increase in the recognition latency of object triads as the orientation in which they were presented became increasingly disparate from the orientation in which they were originally studied. The predicted results are that navigation will not show alignment effects and that learning conditions using a single orientation will show such alignment effects.

Virtual worlds are a new training condition that can be programmed to take on the dimensions and attributes of any real-world environment. Size, complexity, storage, and alteration of the training environment are each easily dealt with by training programs using VEs. Prior research in real and virtual environments has shown that spatial knowledge gained from navigation primarily leads to knowledge about routes (Thorndyke & Hayes-Roth, 1982), whereas spatial knowledge gained from a map primarily leads to knowledge about configurational layout. Prolonged navigation can lead to configurational knowledge that is superior to that attained by map study alone (Darken & Sibert, 1996). Although we do not include a real-world viewing condition as has been done in our previous work (Arthur, Hancock, & Chrysler, 1996), we hypothesize that training in the VE navigation group will yield responses similar to those seen in real-world navigation, and significantly different results from responses yielded using a map for training.

While prior research strongly supports the contention that mental rotation is responsible for alignment effects in internal spatial representations from maps and navigation in the real and virtual world, this study is unique in that it explores alignment effects for an egocentric virtual scene from a single viewpoint. To examine the effects that using single and multiple viewpoint VE displays has on alignment effects, the single-viewpoint map group, which is known to produce powerful alignment effects, serves as the baseline for comparison. While a fourth group consisting of a multiple-viewpoint map display could also have been employed, it was not our intention to show that VEs are preferable over these other types of map displays. So, the map group served as a confirmation of alignment influences and thus as a baseline condition. Further work could certainly explore the alternative of such map-based approaches but this is not the crucial issue in the present work.

3. EXPERIMENTAL METHOD

3.1. Experimental Participants

The participants were 21 undergraduate and graduate students at the University of Minnesota. There were 9 women and 12 men between the ages of 18 and 33. All participants had normal or corrected to normal vision.

3.2. Experimental Apparatus

The VEs were constructed using Iris Performer and presented using a Silicon Graphics Onyx Reality Engine minisupercomputer. Participants wore a Kaiser Electro-Optics VIM 1000 Hrpv head mounted display (HMD). The HMD had a resolution of 800 × 600 pixels and with 30 degree vertical × 100 degree horizontal field of view. Head tracking was accomplished with an Ascension “Flock of Birds” tracking system. Locomotion through the VE was accomplished with a Spaceball 2000, six degree of freedom input device. The VE system ran at 30 Hz. The map conditions were conducted using the map shown in Figure 1. Nine objects were represented on the map. The nine objects were a shark, truck, man, ship, dinosaur, blimp, plane, car, and cow. The arrangement of these objects is shown in Figure 1. Participants were instructed to use the center of the object as its specific location in space for test items.

The VE for the multiple-viewpoints (navigation) and single (fixed) viewpoint conditions contained three-dimensional graphic representations of the same nine objects. Objects were scaled to appear full-size. The objects in the VE conditions were situated on a green plane that matched the relative size of a green box that surrounded the map. The orientations of the single fixed viewpoint and the map were the same.

3.3. Experimental Design

The primary manipulation in the present work was the viewing conditions, which were a map versus a single fixed perspective (SFV), each compared with a multiple perspective viewpoint where the latter two were each enacted in a VE. These group effects were between-subject as was participant gender. Twenty-one participants were randomly assigned to one of three environmental learning groups (VE, SFV, or Map). Three dependant variables were measured: mean response latency in judging the correctness of triads, the accuracy of those responses, and the number of trials needed to draw the original object arrangement to criterion during training.

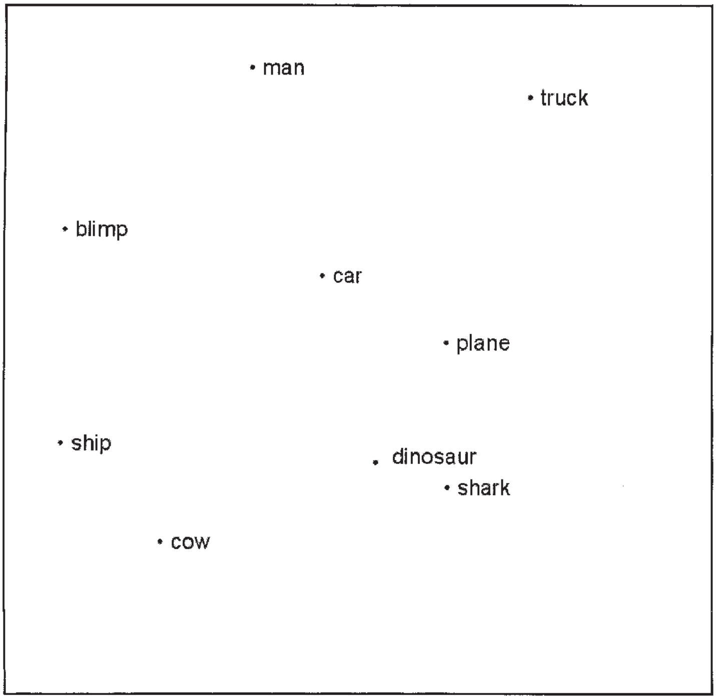

FIGURE 1 Spatial layout of the nine objects in the experimental environment.

3.4. Experimental Procedure

Participants in all conditions were first given 20 minutes experience in a different VE to familiarize themselves with locomotion and orientation procedures and to allow them to experience VE in general. After the VE training, participants were offered the opportunity to rest. Participants in the VE navigation condition were restricted to the ground level and the bounds of the ground plane. Participants in the single fixed VE viewpoint condition were allowed to change their heading and pitch, but not their x, y, z, or roll coordinates. Participants in the map condition were given a map of the environment and not allowed to change the map orientation.

Instructions for all groups were the same. Participants were instructed to study the spatial layout of the objects so that they were subsequently able to draw a map of the object's position. Participants were also informed that the object names would be provided in the map-drawing phase so they should not be concerned about memorizing the names of objects per se, only their location. Participants were given two minutes to view the environment. They were given a map with a border that represented the ground plane and a list of the nine objects from the environment. Participants were told to draw a dot that represented the center of each object and to label the dot.

Following the map drawing, the accuracy of the relative object locations was assessed and the participants were told whether the map was correct or not. The criterion was to correctly represent the interrelationships between the nine objects; for example the man had to be the topmost object on the map (see Figure 1). If the map was not drawn to criterion, participants were only informed that their drawing did not yet sufficiently reflect the layout of the objects and were asked to study the environment for another 2 min. This study and test procedure continued until the map had been twice reproduced correctly but not necessarily on consecutive trials (see also Morrow, Bower, & Greenspan, 1989; Morrow, Greenspan, & Bower, 1987). Following the map-completion task, participants were asked to make judgments between triads of objects from the previously learned environment. Seventy of the eighty-four possible unique triads were randomly selected for use in the task. Triads were shown on a microcomputer that recorded response accuracy and the response time. The participants were instructed to indicate whether the relationship between the triad of objects was correct or not by pressing one of two keys. Participants were instructed to respond as quickly and as accurately as possible. Thirty-five of the triads were correct and thirty-five were incorrect. The incorrect triads were mirror reversals of the correct triads on the vertical axis. One correct and incorrect triad was shown at each of the seven rotation angles (0, 30, 60, 90, 120, 150, and 180 degrees). Participants were allowed to complete a trial run of the computer program using a triad of three states of the United States in the seven orientations to familiarize themselves with how the program functioned. Participants were debriefed following the completion of all triad comparisons.

4. EXPERIMENTAL RESULTS

The results of the triadic judgments were analyzed by a repeated measures analysis of variance (ANOVA). In order to avoid bias between the response latency distributions for men and women, all data points that were greater than two standard deviations above or below the mean response time were discarded. The mean response latency at each of the seven rotations was calculated and subjected to the ANOVA. Gender was not a significant factor in any of the present analyses. To further examine the relationship among viewing conditions, planned comparisons involving linear regressions were used to predict response latencies for the three treatment groups using gender and rotational orientations as independent variables. As illustrated in Figure 2 by the slopes of the lines for response latency, these analyses yielded R^2s of .56, .34, and .01 for the map, SFV, and VE conditions, respectively. A 95% confidence interval for the regression lines slopes included zero only for the VE group; both of the other group confidence intervals were positive and did not include zero.

Error was analyzed using a repeated measures ANOVA using the differentiation previously noted. The effect of treatment group approached traditional levels of significance $p < .08$. The rotation angle factor was significant $F(6, 102) = 5.191, p < .001$, and a subsequent polynomial contrast revealed a significant linear component $F(1, 17) = 11.19, p < .01$. The number of errors increased in a linear fashion as both the rotation angle and response latency increased. Overall the error rate was high at 17% and the percentage of errors increased to 30% at the 180-degree rotation angle, suggesting that the participants found the task moderately difficult. The number of trials that a participant needed to reach the criterion level of performance was also recorded and subjected to ANOVA. The group factor was significant $F(2, 20) = 8.86, p < .003$, and these results are illustrated in Figure 3. Post hoc tests using Tukey's honestly significant difference (HSD) showed that the differences between the map and the VE, and the SFV and the VE were significant, $p < .05$. The difference between the SFV and the map failed to reach significance.

5. DISCUSSION

The results confirmed that learning an environment from only a single view results in an orientation specific mental representation, while conversely, learning an environment from

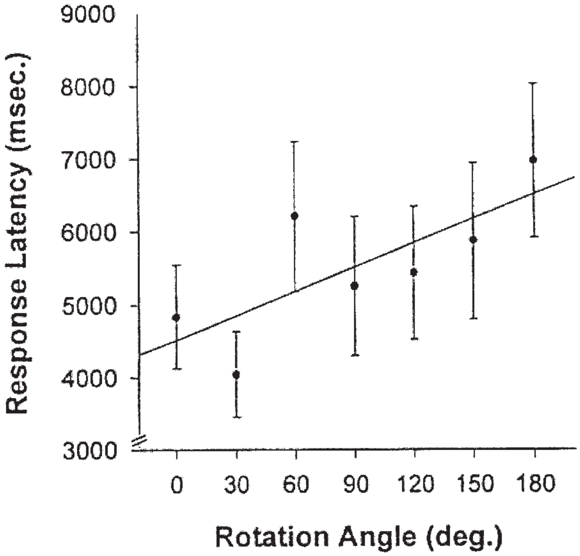

FIGURE 2A Mean and standard error of response latency in milliseconds plotted against the degree of rotation angle for the Map Group.

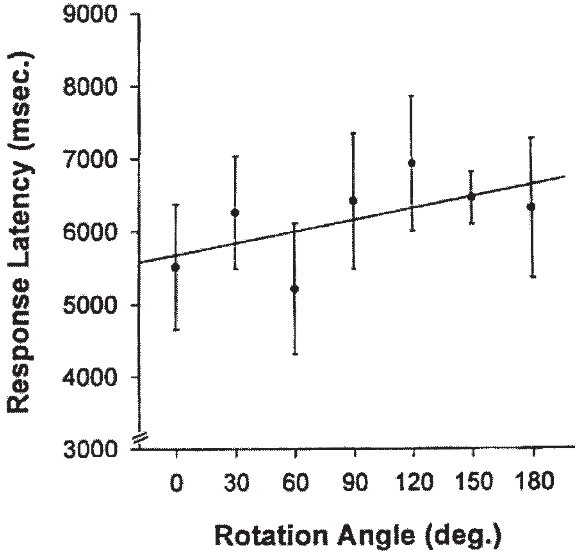

FIGURE 2B Mean and standard error of response latency in milliseconds plotted against the degree of rotation angle for the Single Virtual Viewpoint Group (SFV).

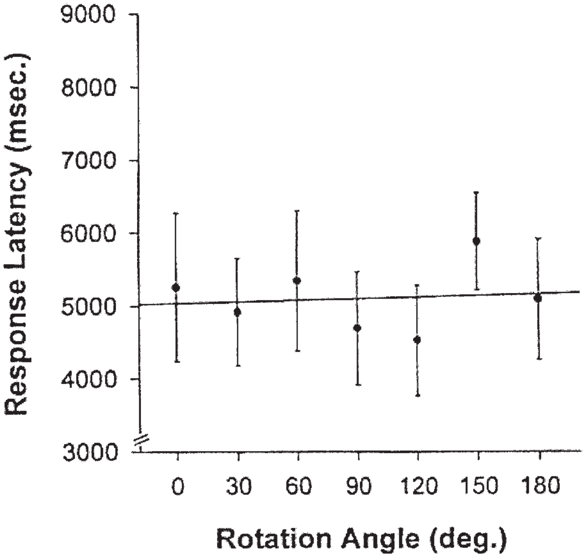

FIGURE 2C Mean and standard error of response latency in milliseconds plotted against the degree of rotation angle for the Free Virtual Environment Group (VE).

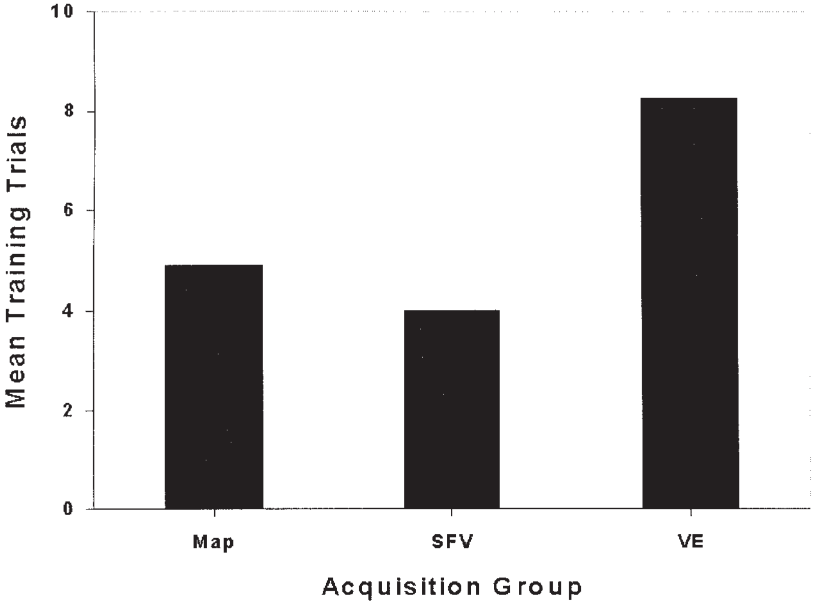

FIGURE 3 Main Effects in Training Trials for the Three Acquisition Groups.

multiple views results in a nonorientation specific mental representation. This finding parallels previous results concerning the differences between maps and navigation in the real world (Evans & Pezdek, 1980; Thorndyke & Hayes-Roth, 1982). Evans and Pezdek found a linear relationship between environments learned with a map and degree of rotation of a triadic accuracy judgment. For environments learned via a navigational or exploratory experience, Evans and Pezdek failed to find a linear function that fit the data. Participants in the navigational condition did not exhibit the linear increase in response latency for the triadic accuracy judgments. The difference between the two groups was attributed to mental rotation and the idea that the navigational participants had multiple perspectives stored in memory for the environment. The results of this experiment support the line of reasoning of Evans and Pezdek.

This experiment also supports the multiple views theory of Tarr and Pinker (1989). The multiple view proposition predicts a linear increase in judgment time as the amount of mental rotation of the stimulus increases. Participants who learned a space via navigation would have multiple stored perspectives of the experimental environment and thus these participants would not have to perform as much mental rotation as those who learned the same space from a single perspective. In our experiment, the VE condition would result in participants with multiple stored views of the environment, while the map and the SFV participants could acquire a representation of only a single perspective. Parenthetically, this leads to a further research problem concerning how many perspectives are necessary to construct an orientation-free representation, which merits further study.

Participants in the VE condition had the highest mean number of training trials, and therefore, it was assumed that initial learning from this environment was much harder than the other two conditions. This difficulty could be attributed to two aspects of our VE system. The first reason was that the participant was able to shift their heading independently of physical body movement. Thus there was no consistent mapping between facing a particular direction and the object that was directly in front of them. Rieser (1989) has shown that the transformation of a mental representation of a space is much slower when the space is rotated mentally (e.g., turn to the left) than when physical locomotion is employed (actually turning to the left). Consequently it might be posited that the representation is not rotated unless the constraints of the task preclude physical rotation, thus forcing mental operation even when the rotation is costly in terms of mental workload, and this is a directly testable hypothesis. The second reason might be that the criterion task favored the map and the SFV conditions. A different criterion task such as distance estimation between pairs of objects might favor the VE condition over the other conditions.

The results of this experiment and others (Arthur, Hancock, & Chrysler, 1996) suggest that spatial learning through exploration of VEs results in a representation that is similar to that attained from a real-world environment. It is expected that factors such as the visual congruency between the real and virtual environment raise concerns about scaling when going from VEs to real-world situations. However, the relative distance and object locations are accurately learned with training in VEs and thus significant transfer may be anticipated. VE therefore offers an effective alternative training method especially when spatial knowledge is an intrinsic component of the training task. Unlike training in conjunction with map learning, VE training allows the user or trainee to form an integrated, flexible, and nonorientation specific representation of space, much like the representation one forms when navigating in any real-world space. While VE training offers a great deal of potential, there is also an important caveat that should be noted. Navigation is easiest to perform when the VE is consistently mapped to the physical body heading. Data from this work suggests that an inconsistent coupling between physical body position and virtual heading may result in increased difficulty in learning a spatial layout. Navigation should be much easier to perform if this constraint is met because there will be no need for users to keep track of where a location is with respect to other locations. When such questions are resolved we anticipate that VE training facilities will provide significant real-world benefits for operations in any number of practical realms.

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