Using a Large Projection Screen as an Alternative to Head-Mounted Displays for Virtual Environments

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ABSTRACT

Head-mounted displays for virtual environments facilitate an immersive experience that seems more real than an experience provided by a desk-top monitor [18]; however, the cost of head-mounted displays can prohibit their use. An empirical study was conducted investigating differences in spatial knowledge learned for a virtual environment presented in three viewing conditions: head-mounted display, large projection screen, and desk-top monitor. Participants in each condition were asked to reproduce their cognitive map of a virtual environment, which had been developed during individual exploration of the environment along a predetermined course. Error scores were calculated, indicating the degree to which each participant's map differed from the actual layout of the virtual environment. No significant difference was found between the head-mounted display and large projection screen conditions. An implication of this result is that a large projection screen may be an effective, inexpensive substitute for a head-mounted display.

Keywords

Experiment, virtual reality, spatial knowledge, field of view, cognitive map, head-mounted display, projection screen, monitor.

INTRODUCTION

The acquisition of spatial knowledge for an unfamiliar physical environment progresses through three stages. In the first stage, people learn the locations of landmarks. This is referred to as *landmark knowledge*. As they learn to navigate from place to place in the environment following familiar paths, people gain *route knowledge*. Finally, *survey knowledge* for the environment is achieved—knowing the way around well enough to have a mental (or cognitive) map of the environment [6].

Virtual reality (VR) provides an opportunity for people to gain spatial knowledge for an environment other than the one in which they are physically located, and therefore has the potential to be an invaluable educational and training tool [15]. VR allows students to explore different perspectives of physical and spatial relationships that are hidden in a 2-dimensional textbook [1]. Military training for dangerous missions can take place in a VR environment without threat of physical harm [10]. Acquisition of spatial knowledge for a virtual environment has been shown to follow the same three stages as for a physical environment: configurational knowledge, route knowledge, and survey knowledge [18]. However, in order for a VR experience to seem the most realistic, an immersive experience in a head-mounted display is necessary [8].

Previous research has explored the degree of spatial knowledge that can be acquired from still images projected onto a surface compared with spatial knowledge of the real world [7]. The differences in spatial knowledge between head-mounted displays and monitors for viewing virtual environments have also been studied [18]. This study was designed to augment prior work by investigating the perception of physical relationships between landmarks in a virtual environment and the acquisition of survey knowledge under three viewing conditions: head-mounted display, large projection screen, and desk-top monitor.

Spatial Cognition

Cognitive maps—internal (mental) representations of spatial environments—are a component of spatial knowledge [9]. This internal representation is the basis for human interaction with the world, guiding people’s decisions and interactions [6]. Spatial problem-solving activities such as wayfinding and navigation rely heavily on cognitive maps, which act as internal conceptualizations of the problem to be solved.

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Cognitive maps are more accurate when they are formed by viewing a paper map of an environment than from navigation through the environment. However, repeated navigation in the environment results in a cognitive map that is as accurate as if it was learned from a paper map[20].

People develop cognitive maps for a virtual environment in a similar manner to the way they do a real-world environment. One way to measure differences that occur in cognitive maps arising from experiencing virtual versus real environments is by asking people to estimate distances between landmarks. Previous research has examined the accuracy of distance judgments in both physical and virtual environments.

Distance judgments from the real world are not perfect; they are generally 87-91% of actual distances. People are significantly less accurate at estimating distances when viewing a virtual environment [22,11]. Head-mounted displays produce cognitive maps that perform significantly better than cognitive maps from monitors, due to the additional perceptual cues provided by peripheral vision and the ability to look around. Peripheral vision plays a critical role in the understanding of the spatial layout of an environment [18,19].

Field of view, measured in degrees, indicates how much of the world can be seen at a given time. For example, someone looking through a window towards the outdoors has a more restricted field of view than someone who is actually standing outdoors because the edges of the window make the visual field smaller. Field of view has a large impact on the underestimation of distances, both in the real world and in a virtual environment [2,3]. A smaller field of view results in compression of distance judgments—people think things are closer than they actually are. Hagen (1978) hypothesized this is because people underestimate the unseen foreground distance between themselves and what they are viewing.

Education and Training

An immersive experience can be described as one in which a person is enveloped in a feeling of isolation from the real world. One can feel immersed in movies where interaction is not possible, as well as in video games, which allow a high degree of interaction. In a virtual environment, having a task to perform increases the feeling of immersion.

A different, but related aspect of a virtual experience is presence: the extent to which a person's cognitive and perceptual systems are tricked into believing they are somewhere other than their physical location [22]. Display devices that evoke a great sense of presence often cause simulator sickness (a variant of motion sickness); symptoms include loss of skin color, dizziness, nausea, and vomiting [12].

It is important for educational and military training applications of VR that spatial knowledge learned is as accurate as possible so that the information learned will transfer to a real environment [21]. Head-mounted displays are generally seen as the most effective way to gain accurate spatial knowledge from a virtual environment. However, the equipment required can be prohibitively expensive and uninviting. In addition, simulator sickness can result from exposure to a head-mounted display [15].

Educational benefits of VR include the ability to interact with and manipulate objects, and the potential to experience environments that are too dangerous in the real world. It is possible to simulate an environment where constraints of the physical universe do not apply [10]. Also, enthusiasm for VR among children is high might encourage passive learners—those that tend not to make decisions while learning—to become more proactive through the potential for interactivity [1].

This paper examines differences that occurred when study participants traveled through a virtual environment viewed in a head-mounted display, on a 3.35 m wide x 2.30 m tall projection screen, or on a desk-top monitor. Data consisting of judgments of the relative position of landmarks in the virtual environment was gathered after participants had experienced it. The data was then analyzed to determine its accuracy or inaccuracy when compared with the actual layout of the virtual environment. [5,17]. Participants' survey knowledge was expected to be more accurate when the environment was viewed in a head-mounted display than projected onto a screen, and least accurate when the environment was displayed on a desk-top monitor.

METHOD

Participants

Students and staff members were solicited from the University of Pittsburgh and Carnegie Mellon University in Pittsburgh, Pennsylvania. Potential participants completed a questionnaire to determine their eligibility to participate in the study. Participants were excluded from the study if they reported any of the following characteristics:

- training or professional experience in a field such as architecture, mechanical or civil engineering, or industrial design
- vision that was not correctable to 20/20
- played any first-person navigation-based video games (e.g. Quake) more than 5 hours per week or 20 hours per month
- reported wearing a head-mounted display more than twice per year

Eligible participants fell within the age range of 18 to 33 years old and were randomly assigned to one of three conditions: Screen, Monitor, or Head-Mounted Display (HMD). 67 participants completed a pre-test of their spatial perceptual abilities. Data from 19 participants scoring more than one standard deviation from the mean in either direction was excluded from the statistical analysis of the experimental results. The remaining 48 participants were balanced for gender and age in each condition. The experiment took 40 - 55 minutes to complete, and each participant was paid $10.00.

Apparatus

Hardware and Software

All participants were asked to navigate through two virtual environments. The environments were created using Alice, a freely available VR authoring and playback tool [14]. A Windows 95 Pentium II 300 MHz computer equipped with 128MB of RAM and two video cards was used to run the Alice software during the experiment. The computer's main video card (a Nvidia RIVA 128) was plugged into a standard desk-top monitor so the experimenter could start Alice and load the virtual environments. Meanwhile, Alice sent the output of the virtual environment to the second video card (a Diamond Monster 3D II) that was used to drive one of the display devices (head-mounted display, projection screen, or desk-top monitor).

Display Devices

The HMD condition used a Visette Pro head-mounted display with Ascention SpacePad tracking system (see Figure 1). Tracking devices for the head-mounted display were mounted to a cardboard square and suspended from the ceiling approximately .5 m from the participant's head when seated. The head-mounted display was placed on the participant's head by an experimenter with experience in fitting these devices, and time was taken to ensure that the equipment did not strain the participant's neck or bind too tightly. Field of view for this device was 60° horizontal x 46.8° vertical, which was matched in the Monitor and Screen display conditions.

The Monitor condition used a standard 21" (53 cm) computer monitor (model Iiyama Vision Master 500) raised to eye level and positioned closely on the table in front of the participant at the appropriate height.

The Screen condition used a rear-projection screen apparatus, consisting of a Toshiba TLP511A projector, a mirror used to increase the projector's throw distance, and a 3.35 m wide x 2.30 m tall screen (material custom-manufactured by Gerriets International of Revue). When mounted in the experiment room, this screen spanned floor to ceiling.

Figure 1: head-mounted display

Navigation Device

Previous spatial cognition research has taken one of two approaches to the issue of navigation in a virtual environment: either participants are allowed to freely explore or they view a scripted presentation of a virtual environment. This study combined those approaches by allowing participants the freedom to navigate; yet the experimenter verbally led them through a scripted sequence of actions. A steering wheel was used to control navigation, rather than a mouse or joystick. This decision was motivated by a desire to provide a method of interactivity that would be easy to learn, and thus enhance the reality of the virtual experience [8]. Participants used a Thrustmaster Grand Prix steering wheel game controller, which allowed car-like steering (see Figure 2). The wheel had two levers that could be grasped by the fingertips of each hand while steering and used to propel the participant forward or backward in the virtual environment at a constant speed.

Procedure

The experiment consisted of a standard spatial ability pretest, exploration of two virtual environments, and a posttest to discover what participants could remember about locations of landmarks in the second, experimental virtual environment.

Pretest

The experiment took place on the Carnegie Mellon University campus. Upon their arrival, participants were asked to complete the Educational Testing Service "Surface Development Test—VZ3," an instrument to measure ability for mental manipulation of 2-dimensional landmarks into 3 dimensions [4]. Participants were shown several line drawings (see Figure 3) and were required to visualize how the items depicted might be folded to form a 3-dimensional shape. This particular test was chosen because the posttest (described below) draws upon similar cognitive abilities [3]. Data from participants scoring more than one standard

Figure 2: steering wheel

deviation from the mean in either direction was excluded from the statistical analysis of the experimental results, in an effort to control for variability in the sample.

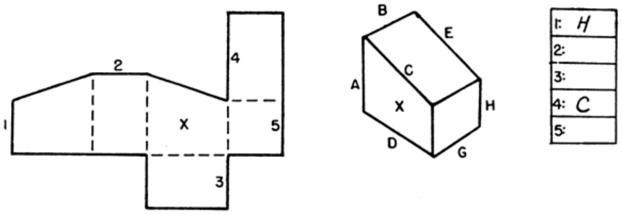

Figure 3: practice problem from the ETS "Surface Development Test—VZ3"

Exploration

After completion of the pre-test, participants were led to the location of the equipment for displaying the virtual environments. For the Screen condition, this room contained the previously described screen apparatus at a preset distance from the chair where participants sat. For the Monitor condition, a computer monitor was placed on a table in front of the chair. For the HMD condition, participants were shown a head-mounted display, and its function was explained. Then the experimenter fit the head-mounted display device to a participant's head. Because nausea was a concern, and because higher temperatures can promote motion sickness while viewing a virtual environment [13], two box fans were used to blow air on participants in all three conditions. Navigation through the virtual environments was restricted to ground-level navigation; that is, participants were not able to fly.

Practice Environment

Figure 4: Entrance booth

Participants first experienced a practice virtual environment, so that they could learn how to use the steering wheel for navigation. A second purpose for the practice environment was to ensure that participants were able to recognize a landmark they would later see in the experimental environment, called an entrance booth (see Figure 4). As explained below, the entrance booth was an integral part of the task to be performed in the experimental environment. The practice environment consisted of an intersection between two streets in an urban setting. Aside from the entrance booth, it bore little resemblance to the experimental environment; however, the method of interaction was identical. Participants were instructed in the use of the steering wheel, placed in the practice environment, and encouraged to freely explore. The practice session continued until the participant indicated that he or she was comfortable with the wheel and levers, approximately 3 -5 minutes.

Experimental Environment

The experimental virtual environment consisted of a virtual amusement park, created for this study. It bore no similarity to a real-world amusement park. The park contained a total of 10 rides and attractions. Attractions in the amusement park were arranged to approximate the appearance of a real amusement park (see Figure 5). Care was taken to ensure that the virtual environment had sufficient complexity to avoid a ceiling effect [17]. Participants were asked to imagine that they were the groundskeepers of the park, and were responsible for driving through it on a golf cart each morning to turn on the rides. This was accomplished by navigating into close proximity to an entrance booth, which was present in front of each attraction. When a participant moved close enough to a ride's entrance booth to activate the ride, a particular sound was played and the participant received visual feedback that the ride was activated.

To ensure that participants would recognize and understand the names used for the rides in the amusement park, a color printout consisting of images of all ten rides along with their names was shown to participants. Prior to participants' interaction with the experimental environment, the experimenter pointed to each image on the printout and spoke the name of the ride aloud. Finally, participants were instructed to pay close attention to the location and orientation of the entrance booths, because they would be asked to recall them later.

Participants then began interacting with the virtual amusement park. The experimenter proceeded to read aloud step-by-step instructions regarding which ride to turn on next. These instructions provided enough information to allow most participants to find the next ride with little

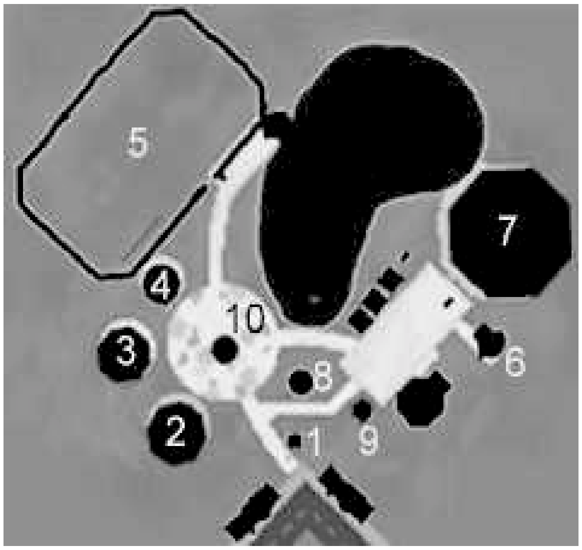

Figure 5: Layout of the Virtual Amusement Park
1 - Park Entrance; 2 - Teacup Ride;
3 - Octopus Ride; 4 - Swings; 5- Roller Coaster;
6 - Lion's Head Skyway; 7 - Haunted House;
8 - Fountain; 9 - Double Ferris Wheel; 10 - Carousel

trouble. However, in the few cases where participants appeared to be struggling or asked for help (e.g. they forgot what the Teacup Ride looked like), the experimenter assisted them by describing the ride's appearance or instructing them to "turn left" or "turn right." The experimenter was careful not to give any verbal associations between landmarks that might affect the formation of participants' cognitive maps [9]. For example, the experimenter might say, "Look to your left to see the Teacup Ride," rather than "The Teacup Ride is just to the left of the Octopus Ride." The final step in the instructions allowed participants to turn around and look at the park one more time before exiting it. While there was no strict time limit in which to complete the instructions, most participants spent 7 to 10 minutes in the virtual amusement park.

Posttest

Finally, participants were escorted back to the room where they took the pretest and presented with a large sheet of white paper (approximately one meter square, completely covering the top of a small table) and ten 3 cm x 3 cm squares (made from foam core). Each square had on it the name of one of the ten amusement park rides and represented the entrance booth for that ride. Participants were allowed to look briefly at the images of the ten rides again, to ensure that he or she could correctly associate names with the rides. They were then instructed to take as much time as needed to place the ten squares on the paper so that the ten rides' entrance booths were represented as they would appear from above. No indication of desired orientation or scale was provided on the paper; participants who asked were told that the squares were not intended to be to scale and that as much or as little of the paper could be used to place the squares.

After this task was completed, participants were asked to complete a questionnaire regarding any illness or discomfort they might have experienced while navigating in the virtual environment. Finally, they were given $10.00 for participating.

After each participant had left, the experimenter traced and labeled the foam-core squares on the white paper. During later analysis, vertical and horizontal reference lines were added to each participant's paper and distances from these reference lines to the center of each square were recorded. This raw data resulted in coordinates for each ride, allowing angles between landmarks and scaled distances to be recorded for each participant.

RESULTS

The hypothesis that the HMD condition would show better performance than Screen or Monitor conditions was not supported. Results indicate no significant difference between HMD and Screen conditions or HMD and Monitor conditions. Screen and Monitor conditions were significantly different.

Data Preparation

For the posttest, we chose to provide for participants a blank piece of paper with no indication of orientation or scale, to avoid influencing participants' cognitive maps [6]. Participants were instructed to re-create the amusement park as it would appear if viewed from above, paying close attention to location of the rides, or landmarks, in relation to each other. Because no scale or orientation information was provided, these reported maps could not be compared directly to the actual layout of landmarks in the virtual environment.

Participants' reported landmark relationships were compared to their true relationships in the virtual environment to determine placement error. Simply comparing the angle between a set of three landmarks accounts for error in relative orientation, however it fails to sufficiently account for error in relative position.

One can normalize for orientation and scale by transforming the reported map to most appropriately match the virtual environment, and then measure errors in relative orientation and position. One possible approach would be to provide participants with the location of two landmarks from the virtual environment, upon which to base the rest of their reported map. While this single given relationship would provide an orientation and scale, it would bias every error calculation. This is undesirable. So, for each landmark pair (${}_{10}C_2 = 45$), we oriented and scaled the reported map until the pair matched its analog in the virtual environment. Distance error was calculated for the remaining eight transformed landmarks. The total error score (360 measurements per participant) evenly weights every landmark relationship.

	n	Mean	Variance
Screen	16	4666.43	986814
Monitor	16	5640.16	3136277
HMD	15	4981.45	1274196

Table 1: mean and variance for normalized error scores

	n	t-value	p-value
Screen x Monitor	16	-1.92	0.068*
Screen x HMD	16	-0.82	0.42
Monitor x HMD	15	-0.23	0.23

* significant at $p < 0.10$

Table 2: results of pairwise unpooled t-tests

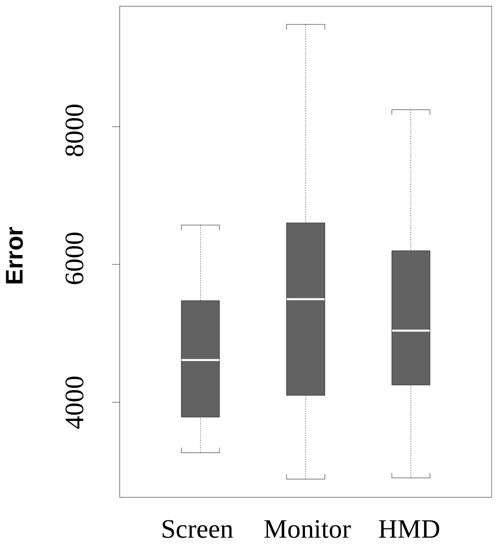

Figure 6: error scores across conditions

Screen vs. Monitor

	Coefficient	Std. Error	t-value	p value
(Intercept)	7493.9277	1422.0577	5.2698	0.0000
Pretest	-39.4142	29.2824	-1.3460	0.1887
Condition[a]	-1029.6199	502.6221	-2.0485	0.0497**

Monitor vs. HMD

	Coefficient	Std. Error	t-value	p value
(Intercept)	6853.9857	1576.8487	4.3466	0.0002
Pretest	-39.1196	32.7696	-1.1938	0.2429
Condition[b]	626.0870	550.6973	1.1369	0.2656

Screen vs. HMD

	Coefficient	Std. Error	t-value	p value
(Intercept)	6940.5775	997.1337	6.9605	0.0000
Pretest	-40.9806	20.6173	-1.9877	0.0571
Condition[c]	-404.8166	372.9730	-1.0854	0.2874

a base case is monitor with coefficient 0
b base case is HMD with coefficient 0
c base case is HMD with coefficient 0
** significant at $p < 0.05$

Figure 7: regression and t-test results

Statistics

Due to equipment failure and a high level of discomfort in the head-mounted display, one participant was dropped from the HMD condition after the experiment had been conducted. Table 1 shows means and variance for the normalized error scores. The mean error score was lowest for the Screen condition, and highest for the Monitor condition, meaning that Screen performed better than Monitor on average (see Figure 6).

After completing descriptive statistics, Bartlett’s Test for homogeneity of variance was performed. Because results for Bartlett’s test were nearly significant ($p = 0.060$), indicating that the variances for the three conditions were too different for an ANOVA to yield useable results, the decision was made to perform more robust pairwise unpooled t-tests.

P-values for the unpooled t-tests show that the difference between the Screen and Monitor conditions is significant at the level of $p < 0.10$ (Table 2 shows the results of the t-tests). Because pairwise t-tests do not take into consideration the spatial pretest as a covariant, a regression analysis was performed, using condition as an indicator variable. After accounting for the influence of pretest scores on the outcome of the posttest, t-values were calculated a second time. The Screen condition was found to significantly outperform the Monitor condition ($p=0.0497$). There were no other significant differences. A complete report of the analysis can be found in Figure 7.

Discussion

Results indicate that there is little difference in survey knowledge for a virtual environment as viewed through a head-mounted display or projected onto a large screen. Even with a head-mounted display's increased peripheral vision and capability to allow a participant to freely look around the virtual environment, this study found that the large screen still leaves participants with comparable spatial knowledge. While contrary to the original hypothesis, this result is consistent with Johnson (1999) who found no significant difference between a head-mounted display and a projection screen used to train soldiers to navigate an unfamiliar environment.

The unexpected absence of a significant difference between the HMD and Monitor conditions also contradicts the original hypothesis. The belief that the HMD condition would perform significantly better than either of the fixed-display conditions (screen, monitor) was based on the head-mounted display’s additional display capabilities. By allowing the participant to turn their head, he or she could gain a greater sense of presence and potentially take in more information from the environment. However, it was consistently observed that participants in the HMD condition did not turn their head very much, as previously reported by Pausch (1996). This unintended reduction of the head mounted display to a fixed display could account for the lack of significant difference. Also, negative aspects of the head-mounted display (e.g. weight, low acuity) could possibly account for the higher mean error score in the HMD condition as compared with the Screen condition.

While variances in the Screen and HMD conditions were similar, the variance in the Monitor condition was found to be significantly different. A possible explanation for the greater variance observed in the Monitor condition lies in the relationship between field of view and judgments of distance. Participants' seated position when viewing the monitor was not artificially fixed, and it is possible that movement forward or backward from the display might have had altered their field of view, causing differences in their interpretation of the spatial relationships between landmarks in the experimental environment.

The difference in error scores between the Screen and Monitor conditions was statistically significant. In addition, based on regression of Screen vs. HMD, the negative coefficient value (while not a significant difference) might be an indication that participants in the Screen condition tended to perform better than those in the HMD condition. What caused the screen to outperform the other two conditions? It is possible that a large image engenders more presence by tricking a person's perceptual systems into thinking they are really there, a phenomenon that is normally associated with HMD but not with flat displays. Images projected onto the screen may have been big enough to appear real, and therefore promote more accurate judgments of relative position.

This finding suggests an intriguing conclusion; that the low-cost projection screen might be as effective as a head-mounted display for educational or training exercises involving spatial cognition. The screen cost only $400 to build, while the head mounted display equipment used has a purchase price of approximately $6000. While the projector used in the Screen condition was quite expensive, it was possible to use it with a minimal amount of effort. Head-mounted display equipment is much more labor-intensive to install, as well as being invasive and uninviting technology to use. These advantages, combined with the lower incidence of discomfort due to simulator sickness, make the use of a large projection screen an attractive alternative to head-mounted displays.

Additionally, this study opens up many interesting avenues for future work. While viewing a virtual environment in a head-mounted display is a single-user experience, using a large projection screen has the potential to facilitate multi-user experiences. It is unknown at this time the whether multiple participants run simultaneously would have gained the same degree of survey knowledge as the participant who was driving. While there is no quantitative data to support the observation that participants generally did not look around when in the head-mounted display, a new study examining the impact of spatial cognitive ability and high vs. low head motion on survey knowledge for a virtual environment could produce interesting results.

Finally, an important area of research is the transfer of spatial knowledge from virtual to real environments. If indeed a large projection screen is a suitable substitute for head-mounted displays, it will be important to discover to what extent spatial knowledge learned from a virtual environment projected onto a screen is accurate in the real world.

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