Comparison of Path Visualizations and Cognitive Measures Relative to Travel Technique in a Virtual Environment

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Abstract—We describe a between-subjects experiment that compared four different methods of travel and their effect on cognition and paths taken in an immersive virtual environment (IVE). Participants answered a set of questions based on Crook's condensation of Bloom's taxonomy that assessed their cognition of the IVE with respect to knowledge, understanding and application, and higher mental processes. Participants also drew a sketch map of the IVE and the objects within it. The users' sense of presence was measured using the Steed-Usoh-Slater Presence Questionnaire. The participants' position and head orientation were automatically logged during their exposure to the virtual environment. These logs were later used to create visualizations of the paths taken. Path analysis, such as exploring the overlaid path visualizations and dwell data information, revealed further differences among the travel techniques. Our results suggest that, for applications where problem solving and evaluation of information is important or where opportunity to train is minimal, then having a large tracked space so that the participant can walk around the virtual environment provides benefits over common virtual travel techniques.

Index Terms—Evaluation, information visualization, navigation, virtual reality.

✦

1 INTRODUCTION

NUMEROUS techniques have been implemented in Virtual Environments (VEs) to allow a participant to move about a virtual space. In general, they can be categorized as either techniques that try to replicate the energy and motions of walking or as purely virtual travel techniques. Examples of the former include treadmills [1], [2] and walking in place schemes [3], [4], [5]. Examples of the latter usually use a joystick to "fly" through a space in a direction specified by either head orientation or a handheld pointer [6]. All of these approaches assume that the physical tracked space available to the user is smaller than the virtual space that is to be experienced. However, recent advances in wide area position tracking technology now enable us to track a user's movement through spaces that are much more expansive than the 2-3 meter diameter spaces normally tracked by electromagnetic tracking devices [7]. This upgrade in available technology allows us to create virtual environments that a user can experience by simply walking around in the environment in the same way she would walk around a physical space. It also provides us with the opportunity to measure the relative efficacy of experiencing a space via normal walking versus any of the simulated walking metaphors. Our goal was to investigate the differences on cognition and understanding of a virtual environment when explored using common joystick-based travel techniques versus walking about the space in a natural manner. This paper is an extension of a previous paper published at the IEEE Virtual Reality Conference in 2004 [8].

2 PREVIOUS WORK

Navigation is the most common user action in virtual environments and is divided into a motor component called travel and a cognitive component called wayfinding [9]. Bowman et al. define wayfinding as the cognitive process of defining a path through an environment, thereby using and acquiring spatial knowledge to build up a cognitive map of the environment. Travel, on the other hand, refers to the movement of the viewpoint from one location to another.

Wayfinding issues have been the subject of studies by many [10], [11], [12], [13], [14], [15]. In this study, however, we focus on the travel component of navigation. In the next section, we discuss different travel techniques.

2.1 Travel Techniques in IVEs

Immersive virtual environments (IVEs) attempt to have the user believe they are within the virtual environment. Some IVEs, such as architecture walkthroughs, use a first person perspective [1]. To improve the level of immersion, some virtual environments systems use a tracking system to allow the user to control the viewpoint. Immersion "describes the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding,

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and vivid illusion of reality to the senses of a human participant" [16].

Viewpoint control is usually accomplished by a combination of head motion and by some travel technique that may be entirely virtual (such as a joystick) or that may try to replicate real-world modes of travel such as walking or riding in a vehicle.

Tracking systems used in IVEs report the position and/or orientation of some device (typically attached to the user's head) within some tracking area. Welch and Foxlin provide a comprehensive overview of current tracking systems [17]. We generalize indoor tracking systems for head tracking into three major categories:

1. 3DOF Orientation Only—System reports only the orientation of the device. Examples include: Intersense InertiaCube.
2. 6DOF Limited Area—System reports position and orientation, restricted to some distance (about 6 feet) from an emitter [19]. Electromagnetic and acoustic-based trackers fall in this category. Examples include: the Ascension Flock of Birds and the Polhemus Fastrak.
3. 6DOF Wide Area—System reports position and orientation in a large area, typically room sized. These systems typically require substantial infrastructure (such as fiducal markers). Examples include: 3rdTech HiBall, Intersense IS-900, and the WorldViz PPT.

With any of these tracking systems, if the physical tracked space is smaller than the virtual space, navigation is typically controlled through the use of tracked mice, joysticks, or gloves. But, does this misregistration between the real and virtual world (e.g., the user presses a button to simulate running) hamper the applicability of the virtual environment for learning and training? There have been surprisingly few analytic comparisons reported in the literature of the relative effectiveness of different travel modalities for different types of tasks. The next section outlines some previous studies in VE locomotion.

2.2 Studies in IVEs

Previous studies suggest certain tasks and applications benefit from immersive virtual environments. Pausch showed that search tasks could be done faster in a tracked head mounted display (HMD) versus an untracked HMD [18]. Ruddle et al. found that navigating large-scale virtual environments was significantly faster in a tracked HMD versus a desktop display [20]. VEs are useful in evaluating product designs and assembly verification [21], [22].

Bowman et al. [6] have conducted experiments on virtual joystick-based travel in immersive virtual environments that indicate that "pointing" techniques are advantageous relative to "gaze-directed" steering techniques for a relative motion task. They also report that motion techniques which instantly teleport users to new locations are correlated with increased user disorientation. In the evaluation of systems that try to replicate the energy and motions of walking, the reported sense of presence has been rated higher in real walking and walking in place compared to joystick "flying" conditions [23].

In studies that compared actually walking through a virtual maze to virtual travel, Chance et al. [24] found a significant difference between walking as compared to joystick controlled travel in participants' ability to indicate the direction to unseen target objects from a terminal location in the maze. A secondary finding of this study was that the degree of motion sickness depended upon travel mode, with the lowest incidence occurring in the real walking mode. Mental maps and basic navigation are also improved by real walking [25].

Mania et al. compared recall of different shaped objects in a photorealistic VE displayed on an HMD in mono or stereo, with or without head tracking, and on a desktop monitor with the real-world task situation [26]. They found variations in the distribution of participants' memory awareness states across conditions while, in certain cases, task performance failed to reveal any differences. In addition, they found that experimental conditions which incorporated head tracking were not associated with visually induced recollections.

3 USER STUDY

Cognition is defined as the process of receiving, processing, storing, and using information [27]. As opposed to perceptual motor tasks (e.g., pick up a pen), cognitive tasks require problem-solving decisions on actions (e.g., pick up a red pen).

In this study, we asked the following question:

- Is there an effect on cognition if we explore a virtual space by walking around in a natural manner as compared to using a virtual travel technique?

To investigate this question, we designed a study comparing common travel techniques to actually walking in a large tracked area. The task was to explore a virtual room for five minutes. Participants were told that they would be asked questions about the room at the end of their exploration.

3.1 Study Design and Methods

3.1.1 Participants

The participants were 49 students from the University of North Carolina at Charlotte. Volunteers were recruited from summer school courses, with fliers, and by word-of-mouth. We discarded data from three participants who failed to complete a minimum of 66 percent of the cognition questionnaire, possibly due to loss of interest in the study. In addition, due to procedure failures, cognition questionnaire data from two participants was not collected. This left us with 44 participants' data to be included in the analysis of the cognition questionnaires (11 from each condition) and 46 in the remainder of the questionnaires, sketch maps, and debriefing.

3.1.2 Design

The experiment was a between-subjects design. The independent variable was the travel technique. The dependent variables were performance on a cognition questionnaire and sketch map accuracy. The participants were randomly assigned to one of the four conditions described in the following section.

Fig. 1. Top left: Participant in Monitor condition. Bottom Left: Participant in Real Walking condition. Right: Participant in Virtual Walking condition.

3.1.3 Conditions and Rationale

One of the most commonly implemented methods of locomotion in a virtual environment is to use a handheld button device that moves the user in the direction in which she is looking when a button is pressed. There are several variations to this approach. We can simulate "flying" if we allow the user to move in her look-at direction with no constraints. Virtual "walking" is usually implemented by moving the user in a 2D plane parallel to the ground plane of the environment.

The most common tracking technologies are either six-degrees of freedom (position and orientation) trackers with a limited effective range or three-degrees of freedom (orientation-only) tracking devices. With the former, the user can use normal body motion, such as squatting down or moving the head side-to-side, as she experiences a VE. With the latter approach, the user can change her view of the world by turning her head in a natural way, but her position can only be changed via virtual techniques such as button pushes on a hand-held device.

For this study, we compared the following four conditions:

1. **Real Walking (RW)**—The participant position and orientation are tracked in a physical tracked space the same size as the virtual room (4.5m x 4.6m x 2.6m). The participant walks around the virtual room in a natural manner (Fig. 1).
2. **Virtual Walking using Six-Degrees-of-Freedom Tracking (VW6)**—The participant's head position and orientation are tracked, but the physical tracked space is smaller than the virtual room. The participant uses a wireless joystick to navigate about the room. When a button is pressed, the participant is translated forward or backward (depending on the button) along the participant's look-at vector in a plane parallel to the floor. The participant stands within a 1.2m by 1.2m enclosure that both gives them something to hold on to for balance and simulates the reduced tracking volume of common electromagnetic and acoustic tracking devices (Fig. 1).
3. **Virtual Walking using Three-Degrees-of-Freedom Tracking (VW3)**—The participant's head orientation is tracked. A joystick is used to implement virtual walking. The participant's viewpoint is moved in a plane parallel to the floor of the room. The viewpoint can also be moved up and down relative to the floor of the room with a different set of buttons. The

TABLE 1
Condition Properties

	TrackedDoF	Tracked Volume	Immersive?
RW	6	4.5m x 4.6m x 2.6m	Yes
VW6	6	1.2m x 1.2m x 2.6m	Yes
VW3	3	-	Yes
M	0	-	No

participant stands within the same 1.2m by 1.2m enclosure used in the VW6 condition.

4. **Joystick with a Monitor (M)**—The participant sits in front of a 17-inch flat panel display at a distance such that the field-of-view is equal to the HMD conditions (Fig. 1). She navigates about the room in a manner identical to the VW3 condition (button arrangement, etc.) except that the joystick is now used to control the view direction.

One way to view our choices of what to test in this experiment is as a comparison of cost and capability versus performance. Large area six-degrees-of-freedom (RW) tracking systems are expensive in both monetary and space requirements as compared to orientation-only tracking (VW3). Limited range six-degrees-of-freedom trackers (VW6) are somewhere in between with respect to cost and space. The inclusion of the monitor condition (M) was to give us a degree of "ground truth" for the comparative usefulness of an immersive VE for the tasks that we evaluated. All conditions had a 60 degree diagonal field of view. Table 1 summarizes the salient properties of each condition.

3.2 The Environment and Equipment

3.2.1 Equipment

For the RW, VW6, and VW3 conditions, participants wore a stereoscopic V8 HMD (640 X 480 resolution in each eye) that was tracked by a 3rdTech HiBall 3100 tracking system. The HiBall updates position and orientation at approximately 1.5 kHz. Our HiBall system has a tracked volume of 4.5m x 4.6m x 2.6m. For condition M, we used a 17 inch flat screen monitor. We used a Logitech Wireless Joystick. All the conditions ran on a Pentium 4 Dell PC with an nVidia GeForce4 Ti 4200 graphics card. Condition M ran at 60 FPS, while the three HMD conditions ran between 24-30 FPS in stereo.

3.2.2 Training VE

Immediately before exploring the testing VE, participants practiced navigation in a training virtual environment. The training VE had four different colored cubes at different locations in a single room. We asked the participants to locate and travel to each of these cubes.

3.2.3 Testing VE

The testing VE was a single room measuring 4.5 x 4.6 x 2.6 meters. The experimental VE matched the physical space of the tracking area in our lab. One of the virtual doors was mapped to match the physical door in the tracking area. We

(a)

(b)

Fig. 2. (a) Top down view of testing VE. (b) First person view of testing VE.

populated the room with furniture, pictures, books, magazines, etc. (Fig. 2a and Fig. 2b).

Several objects in the testing VE were grouped into themes: The books were all by Stephen King, the pictures were all of nature, and the magazines were all about golf. In addition, there were several sports items distributed throughout the room.

3.3 Measures

We used the following measures: a cognition questionnaire (CQ) based on a condensed version of Bloom's Taxonomy of the Cognitive Domain [28], a sketch map [29], and the Steed-Usoh-Slater (SUS) Presence Questionnaire [30]. Additional measures were used to help determine if there were any confounding factors affecting the results between the different conditions.

3.3.1 Cognition Questionnaire (CQ)

We created a set of 27 questions to assess the participants' cognition of the VE. These questions were selected and modified from an original set of 37 questions used in a pilot study conducted on 12 participants.

The questions were based on Bloom et al.'s taxonomy [28]. Bloom et al.'s original taxonomy describes six cognitive categories arranged in a hierarchy from simple to complex: Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation. We followed Crooks' condensation of the six categories into three [31]:

- Knowledge: The recall or recognition of specific information.
- Understanding and Application: Combines comprehension (understanding of facts and principles, interpretation of material) and application (solving problems, applying concepts and principles to new situations).
- Higher Mental Processes: Combines analysis (recognition of unstated assumptions or logical fallacies, ability to distinguish between facts and inferences), synthesis (integration of learning from different areas or solving problems by creative thinking), and evaluation (judging and assessing). The questions focused on objects evenly distributed about the room such that roughly the same number and category of questions were asked about each part of the room.

The following are example questions from each category:

1. Knowledge:

   - How wide was the couch?
   - How many darts were in the dartboard?
2. Understanding and Application:

   - What was the common theme of the paintings?
   - How many people are coming to eat? How did you come to your answer?
3. Higher Mental Processes:

   - Name all the objects made out of wood.
   - Given the genre of books in the room, name a book that the residents might buy.

Each question was worth 1 point, for a maximum score of 27. Most of the questions (19) had a single answer for a possible score of either a 0 (wrong) or a 1 (correct). The remaining questions were posed such that an answer could be partially correct or approximately the correct answer. Answers were ranked by how close each participant's response was to the correct answer. We quantized the rankings to these questions and gave scores of 0, 0.25, 0.5, 0.75, or 1.

3.3.2 Sketch Maps

Participants were asked to draw a top-down view, a sketch map, of the testing VE and the objects within it (Fig. 3). Then, each participant's sketch map was given a set of goodness and object positioning scores.

Maps were ranked for goodness on a scale of 1 (poor) to 5 (excellent) by three graders who were blind to subject identity as was done by [29]. The map goodness rating is a subjective measure of how useful the map would be as a navigational VE tool. The graders ignored drawing ability and concentrated on overall room layout accuracy. The final goodness score for a map was an average of the scores given by the three graders.

Maps were also graded on the relative position of the objects within the VE. Each map was given two scores:

- A total object position score based on how many objects in the room were correctly positioned in the sketch. There were a total of 63 objects in the room.
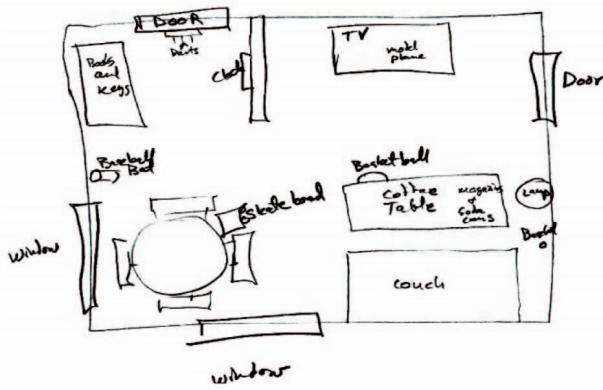
Fig. 3. Sample sketch map.

- A significant object position score based on the five most commonly drawn objects. The significant objects were the sofa, dining table, divider, TV, and the coffee table.

An object was counted if its relative position to other objects in the sketch map was correct. The specific object position was not important.

3.3.3 Other Measures

We measured sense-of-presence using the Steed-Usoh-Slater Presence Questionnaire (SUS) [30], spatial ability using Guilford-Zimmerman Aptitude Survey Part 5: Spatial Orientation [32], simulator sickness using the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [33], and visual memory using the Kit of Factor-Referenced Cognitive Test Factor MV-1: Shape Memory Test [34]. In addition, each participant was videotaped and his/her position and orientation were automatically logged during the experimental session in the VE.

3.4 Experiment Procedures

The pretesting, experiment session, and posttesting took each participant approximately one hour to complete.

3.4.1 Preexperiment

The participant first read the Participant Information Sheet and was asked if she had any questions. She then read and signed the Informed Consent Form. Next, the participant filled out questionnaires about demographics, computer use, computer anxiety, and simulator sickness. She then took the Guilford-Zimmerman (GZ) Spatial Ability test.

3.4.2 Experiment

Next, the participant entered a different area of the lab where the experimenter showed and explained to her the equipment particular to her condition. The participant then was fitted with the equipment and practiced navigation in the training environment.

After the training session, the testing VE was loaded. The participant was asked to explore the environment for five minutes.

3.4.3 Postexperiment

The participant filled out another simulator sickness questionnaire and the SUS Presence Questionnaire. Next,

the participant filled out the cognition questionnaire. She also filled out the visual memory test. She was then asked to draw a top-down sketch map of the VE. Finally, the participant was interviewed by the experimenter to elicit qualitative reactions to the experiment.

4 RESULTS

A multivariate analysis of covariance (MANCOVA) was first conducted on the three categories of the cognition questionnaire, using travel technique as the independent variable and controlling for visual memory. We intended to also use spatial ability as a covariate, but this measure was not correlated with the CQ scores. MANCOVA was deemed appropriate because it accounted for prior differences while determining if there were mean differences among the travel techniques on the CQ categories [35]. A univariate analysis of covariance (ANCOVA) was used for the sketch map scores, controlling for both spatial ability and visual memory. Finally, a one-way-between-subjects analysis of variance (ANOVA) was used for analysis of the remainder of our data [36]. An alpha level of 0.05 was used for significance on all measures.

4.1 Cognition Questionnaire

Although the difference in the total score on the CQ was not statistically significant, the results become interesting when broken down by categories: Knowledge (K), Understanding and Application (UA), and Higher Mental Processes (HMP).

The MANCOVA across conditions for the three CQ categories, with visual memory as the covariate, revealed a significant multivariate effect of travel technique, Wilk's Lamda = 0.56, $F(9, 90) = 2.66$, $p < 0.01$. This means that travel technique had a significant effect on the participants' performance on the cognition questionnaire.

Univariate follow-ups indicated a significant effect of travel technique on the scores of both the UA, $F(3, 39) = 3.63$, $p < 0.05$, and HMP categories, $F(3, 39) = 3.12$, $p < 0.05$, but not on the K category of the CQ, $F < 1$.

Planned contrast tests (α planned $= 0.05/3 = 0.016$) showed that, after adjustment by the covariate, the CQ scores for RW were significantly higher than VW6 and M. The difference between RW and VW3 was not significant ($F(3, 37) = 2.44$, $p = 0.079$).

Scores on the UA and HMP categories of the CQ for RW were significantly higher than those for VW6 ($F(1, 39) = 8.76$, 9.01, respectively, $p < 0.005$). Scores on the UA and HMP categories for RW were also significantly higher than those for M ($F(1, 39) = 7.69$, $p < 0.01$, and $F(1, 39) = 3.93$, $p < 0.05$, respectively). Scores on the UA category for RW were significantly higher than those for VW3 ($F(1, 39) = 5.19$, $p < 0.05$). These results imply that the ability to explore a VE in a natural manner might be beneficial for situations which require problem solving, interpretation, synthesis, or evaluation of information. The adjusted means for UA and HMP by travel technique are shown in Table 2.

The differences in the K category of the CQ was not significant among groups, which indicates that travel technique does not have an effect on the simple recall of objects within a VE.

TABLE 2
Adjusted Means for UA and HMP by Travel Technique

Condition	UA	HMP
RW	4.60	3.69
VW6	2.78	2.36
VW3	3.23	3.04
M	2.96	2.84

TABLE 5
Correlations between Sketch Maps and CQ

		CQ Total	K⁺	UA°	HMP^λ	Map Object
Map Object	Correlation	0.385**	0.145	0.484**	0.302*	1.000
	Significance	0.010	0.348	0.001	0.046	0.000
Map Goodness	Correlation	0.339*	0.248	0.392**	0.096	0.560**
	Significance	0.024	0.104	0.009	0.533	0.000

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

4.2 Sketch Maps

Analysis of the sketch maps revealed that travel technique had a significant effect on sketch map goodness scores. Table 3 shows the adjusted means for the sketch map scores by travel technique. The ANCOVA across conditions for sketch map goodness, with spatial ability and visual memory as covariates, revealed a significant multivariate effect of travel technique, $F(3, 40) = 4.60$, $p < 0.01$. Planned contrast tests, using $\alpha = 0.05$ for significance, showed that the map goodness scores for RW were significantly higher than those in VW3 and M. Table 4 shows the results of these planned contrast tests.

The ANCOVAs across conditions for sketch map total object position scores and significant object position scores were not statistically significant. Object position scores were not statistically different across conditions, indicating that natural walking did not have an advantage over other travel techniques for simple recall of objects and their relative positions within the VE. However, it appears that the ability to walk around naturally in the virtual environment seemed to be useful in terms of forming an accurate mental model of the VE, as depicted by the sketch map goodness scores.

4.3 Correlations between Sketch Maps and the CQ

We found that the participants' performance on the CQ was positively correlated to their sketch map performance. Table 5 summarizes the correlations between sketch map

scores and scores on the three CQ categories. The correlation between sketch map total object scores and the score on the CQ was significant, $p < 0.01$. The correlation between sketch map goodness scores and the score on the CQ was also significant, $p < 0.05$. Both map goodness and total object position scores were significantly correlated to the Understanding and Application scores, $p < 0.001$. Map total object position scores were also positively correlated to the Higher Mental Processes scores, $p < 0.05$. Finally, the correlation between sketch map total object scores and sketch map goodness was significant, $p < 0.001$.

The positive correlation between the CQ and the sketch map scores confirms that the CQ is a valid measure of participant cognition since sketch maps are a well-established measure of cognitive maps [29].

4.4 Other Factors

Spatial ability, computer anxiety, and visual memory were not significantly different among groups. Simulator sickness was also not significant among groups. There was no significant difference among groups in computer use, video game experience, and prior VE experience.

A one-way-between-subjects ANOVA across all conditions for the SUS Presence Means was significant, $F(3, 40) = 5.28$, $p < 0.005$. A post hoc Tukey test revealed significance between all the HMD conditions and the monitor condition (Table 6).

5 OBSERVATIONS

5.1 Interview Trends

Analysis of the postexperience interviews resulted in the following trends:

- When asked "What percentage of the time you were in the lab did you feel you were in the virtual environment?" the mean response of the participants in RW was 69.1 percent (s.d. = 24.9), 52.1 percent in

TABLE 3
Adjusted Means for Sketch Map Scores by Travel Technique

Condition	Map Goodness	Map Sig. Object	Map Object
RW	3.71	5.15	31.27
VW6	2.97	4.09	23.07
VW3	2.38	4.21	23.18
M	2.27	4.01	21.52

TABLE 4
Planned Constrasts Tests for Sketch Map Goodness ANCOVA

Conditions	F	Significance
RW – VW6	2.580	0.116
RW – VW3	7.948	0.007*
RW - M	10.123	0.003**
VW6 – VW3	1.696	0.200
VW6 - M	2.485	0.123
VW3 - M	0.061	0.806

*Significant at the α=0.01 level
**Significant at the α=0.005 level

TABLE 6
Tukey Test SUS Presence Mean

Conditions	P-value
RW - VW6	0.883
RW - VW3	0.999
RW - M	0.004***
VW6 - VW3	0.932
VW6 – M	0.024*
VW3 – M	0.006**

Significant at the *α=0.05 level, **α=0.01, ***α=0.005

VW6 (s.d. = 31.7), 58.1 percent in VW3 (s.d. = 33.7), and 33.8 percent in M (s.d. = 29.9).

- When asked "How long did it take for you to get used to the virtual environment, in terms of navigation and interaction?" the mean response of the participants in RW was 15.5 seconds (s.d. = 18), 54.2 seconds in VW6 (s.d. = 43), 34.8 seconds in VW3 (s.d. = 26), and 117.5 seconds in M (s.d. = 104). These numbers indicate that the participants in the monitor condition found the mode of navigation less intuitive than the participants in the HMD conditions.

- When asked "Do you have any comments on interacting with the environment?" 55 percent of RW participants, 25 percent of VW6 participants, 45 percent of VW3 participants, and 17 percent of M participants reported that they tried to avoid objects.

- When asked "Do you have any comments about the way you navigated in the virtual room?" 0 percent of RW participants, 8 percent of VW6 participants, 9 percent of VW3 participants, and 33 percent of M participants reported that navigation was difficult.

- When asked "What did you think about your experience?" 36 percent of RW participants, 17 percent of VW6 participants, 0 percent of VW3 participants, and 8 percent of M participants thought that the experience was realistic.

5.2 Time in Training

While running the experiment, we noticed that the time taken to perform the training tasks differed for each condition. M participants took a noticeably longer time to train than participants in the HMD conditions. In addition, VW6 and VW3 participants took a longer time to train than RW participants. It was clear that RW participants needed the least time to familiarize themselves with the travel technique, in contrast to participants in other conditions.

6 VISUALIZATIONS

Participants' position and head orientation in both the virtual environment and the real lab were logged during their exposure to the virtual environment. The log data was sampled at the frame rate of the application. In the monitor condition, the data was sampled at approximately 60 FPS and, in the HMD conditions, the data was sampled at approximately 24-30 FPS. At each frame, location, head rotation, and current time were logged for each participant. In addition, in the VW3 and VW6 conditions, the participants' actual position and head orientation within the tracked space were logged. Tags indicating whether the participant was in the training or testing phase were also logged. In the HMD conditions, tracking failures were logged and not included in the path visualization analysis.

6.1 Path Visualization

The log information allowed us to visualize the paths each participant took in the virtual environment. Figs. 4, 5, 6, and 7 show sample path visualizations from participants in each condition. The thin green lines indicate view direction and

Fig. 4. Path visualization of a participant in condition RW.

Fig. 5. Path visualization of a participant in condition M.

the gray lines indicate path. The green sphere shows the participant's start position and the red sphere shows the participant's end position.

In the monitor condition, each participant's eye height was measured and used in the virtual environment prior to starting the experiment. It has been suggested that the head movements of participants captured by the HMD are indicative of the actual direction of gaze, given a small amount of error correction [38]. In conditions VW3 and VW6, participants traveled in their view direction either forward or backward using the joystick. Researchers have suggested that it is more intuitive for participants to travel in their view direction rather than the alternative of separating the head orientation and direction of movement [38]. In addition to the ability to travel in the view direction, participants in condition VW6 were also able to walk in a natural manner within the tracked space. Consequently, in a typical path visualization of a VW6 participant, we can notice that subjects tended to travel to distant spots using their joystick in their view direction (Fig. 7). VW6 participants then stopped and proceeded to explore the local environment, moving around in a natural manner within a small area of the tracker workspace.

Fig. 6. Path visualization of a participant in condition VW3.

Fig. 8. Visualization of aggregate path of RW participants.

Fig. 7. Path visualization of a participant in condition VW6.
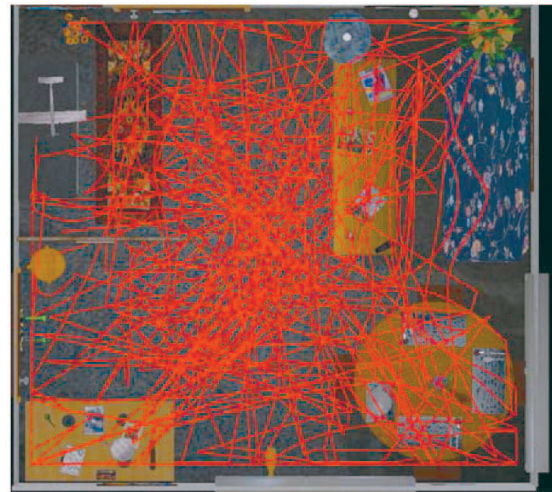

Fig. 9. Visualization of aggregate path of M participants.

Based on the path visualizations we noticed the following:

- Participants in M and VW3 collided with and navigated along the ceiling of the virtual room which gave them a bird's-eye view of the environment.
- RW participants had the least collisions with significant objects, whereas M participants had the most collisions with significant objects.
- Most RW participants leaned over lower objects (such as a coffee table), whereas participants in other conditions collided with these objects.
- VW3 participants did not physically move within the confined space as much as the VW6 participants.
- Path visualizations of RW participants (Fig. 4) are clearly different, in terms of linearity and amount of space covered, from the path visualizations of participants in other conditions.
- VW6 participants primarily used the joystick to get to specific locations within the VE, similarly to M and VW3 participants. Once at the desired location, VW6 participants behaved in the same way as RW participants in that they moved around the tracked space in a natural manner.

6.2 Spaghetti Plot Visualization

We visualized the aggregate paths taken by all the participants in each condition. These paths denoted by the red lines in Figs. 8, 9, 10, and 11 taken for each participant in a particular condition were superimposed upon each other to give us the spaghetti plots. A heavier concentration of lines indicates paths that participants took most often. Most common intersections are denoted by spots where several paths intersect each other.

The path visualizations reveal that conditions involving the use of a joystick show very linear movement traces. Movement traces for condition VW3, VW6, and M are scattered through the virtual environment. Movement traces for RW participants are denser and closer to the center of the room and around the perimeter of objects. RW participants avoided colliding with significant objects. The paths of M and VW6 participants form a crisscross and sporadic pattern of lines, as shown in Figs. 9 and 11. The paths of RW and VW3 participants form distinctive curves of lines that bend around significant objects (Figs. 8 and 10). In the spaghetti plot of the VW3 condition the curve of lines is similar to that of the spaghetti plot for the RW condition.

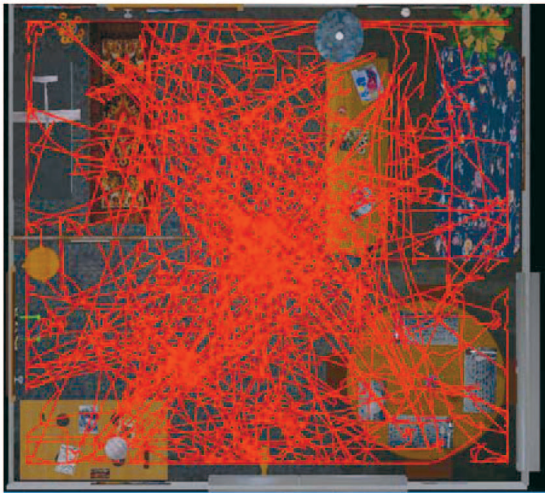Fig. 10. Visualization of aggregate path of VW3 participants.

Fig. 12. Dwell data visualization of RW participants.

Fig. 11. Visualization of aggregate path of VW6 participants.

Fig. 13. Dwell data visualization of M participants. Refer to the legend in Fig. 12.

6.3 Dwell Data

Using participant log files containing dwell data, we created a visualization of where participants spent the most time for each condition, shown in Figs. 12, 13, 14, and 15. A two-dimensional plane was created, divided into sections, and overlaid on a blueprint of the room. The grayscale value of each section represents the degree to which participants "dwelled" in this area for each condition [38]. The grayscale value was calculated for a particular section by subtracting the percentage of time spent in that section from one. The value ranges from white, representing almost no percentage of time dwelling, to black, representing the highest percentage of time spent dwelling. Fig. 12 shows that RW participants spent the highest percentage of time in the center of the room and around the perimeters of the significant objects. The darker areas of Fig. 12 correlate with the heavy concentration of lines in the corresponding spaghetti plot (Fig. 8). In contrast, M participants spent a smaller percentage of time in any single concentrated area and a greater percentage of time throughout the room, along the walls, and in the corners of the room (Fig. 13). In the spaghetti plot (Fig. 9) of the monitor condition, the
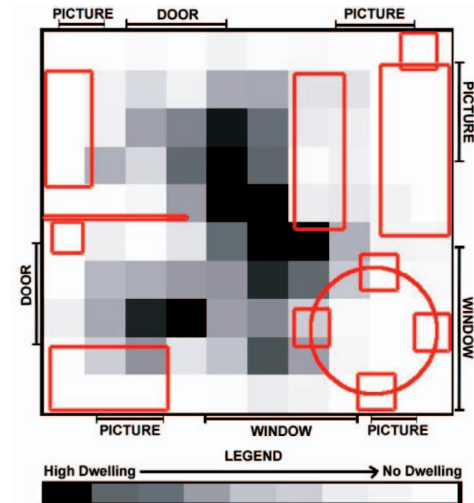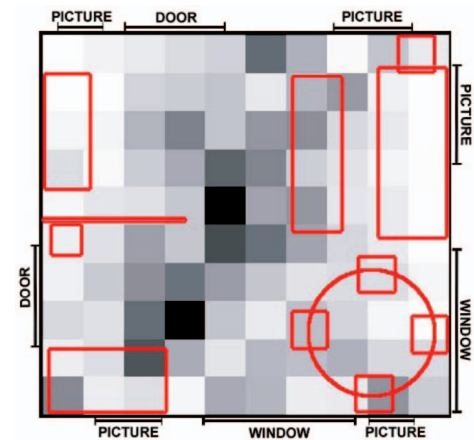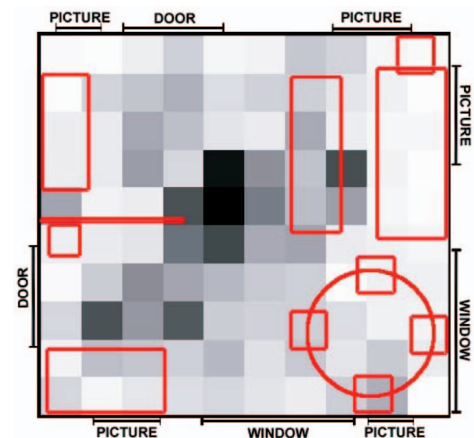

Fig. 14. Dwell data visualization of VW3 participants. Refer to the legend in Fig. 12.

crisscross pattern correlates with that of the darker sections of Fig. 13. The dwell data for VW3 participants (Fig. 14) produced visualizations similar to M participants with a heavier concentration in the center of the room. The dwell data for VW6 participants (Fig. 15) produced visualizations similar to RW participants with more area coverage.
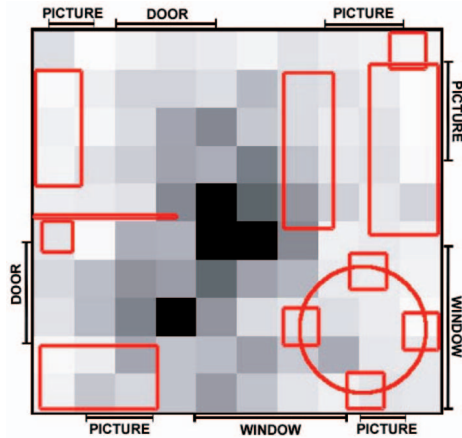
Fig. 15. Dwell data visualization of VW6 participants. Refer to the legend in Fig. 12.

6.4 Analysis of Spatial Variables

In this section, we report on spatial variables computed from each participant's log file data. The variables we computed are total distance covered, horizontal distance covered, and overall head rotation. Quantifying and analyzing these spatial variables allows us to characterize the paths taken by participants in different conditions empirically. The total distance covered was computed by taking the sum of the Euclidean distance between one position frame and the next. The horizontal distance covered was computed by taking the sum of the Euclidean distance between one position frame and the next in the horizontal plane [x, z] only. Overall head rotation was computed as the aggregate of the absolute difference in head rotation in x, y, and z axes between frames. These measurements do not take into account tracking issues such as jitter and lag. Table 7 shows the means and standard deviations of distance and head rotation data for each of the four conditions.

The number of collisions across the conditions could not be accurately calculated since, in RW and VW6, we cannot determine if a participant is colliding with an object or simply leaning over it. For instance, many participants in RW and VW6 were observed leaning over the coffee table to get a better look at the magazines on top.

For data analysis, we used a one-way-between-subjects ANOVA with alpha = 0.05 level of significance. For post hoc analysis, we used the Tukey HSD (Honestly Significant Difference) test. We also used the LSD (Least Significant Difference) post hoc test.

The ANOVA on mean total distance covered was not significant. In the ANOVA on horizontal distance covered, the difference across conditions was significant, $F(3, 40) = 3.41$, $p < 0.05$. A post hoc Tukey test revealed that VW6 participants covered significantly more horizontal distance than M participants, $p < 0.05$. A post hoc LSD test also revealed that VW6 participants covered significantly more horizontal distance than VW3 and RW participants, $p < 0.05$. M participants covered the least distance compared to all other conditions. This result may be due to the unique navigation mode of VW6, where participants are both able

to cover large distances using the joystick and move around naturally within the confined space.

In the ANOVA on overall head rotation, the difference across conditions was significant, $F(3, 40) = 28.92$, $p < 0.001$. A post hoc Tukey test revealed that M participants had significantly more overall head rotation than all the HMD conditions, $p < 0.001$. No significant differences among HMD conditions were observed. This result is expected since all HMD participants had the ability to view objects in the environment though natural head rotation. The mean overall head rotation for the M condition suggests that participants took advantage of the view panning functionality afforded by the joystick to rotate and view objects in the environment. Rotation via joystick allows the participants to easily view the environment using the full 360 degrees and requires less physical effort than moving the head in the HMD conditions.

7 SUMMARY

On the understanding and application category of the cognition questionnaire, participants in RW performed significantly better than all other participants. Participants in RW performed significantly better than participants in VW6 and M with respect to higher mental processes.

Sketch map goodness ratings were significantly higher for participants in RW as compared to participants in VW3 and M. Sketch map scores and scores on the cognition questionnaire were positively correlated, confirming the validity of the cognition questionnaire since it is a novel measure of cognition.

Sense of Presence on the SUS Questionnaire was significantly higher for all the HMD conditions as compared to the monitor condition. There was no difference in sense of presence among any of the conditions in which the participant wore the HMD. During debriefing, there was only a significant difference in Self Reported Presence between RW and M. This difference was strongly supported by comments from the participants during the debriefing session. For example:

- Participant 31 from RW commented "I was afraid to hit my shin on the table."
- Participant 47 from VW6 commented "I almost ran into the divider!"

TABLE 7
Distances Covered and Head Rotation by Condition

Condition	Statistics	Total Distance	Horizontal Distance	Overall Head Rotation
M	Mean	51.45	38.84	1160.12
	SD	27.30	21.30	329.44
VW3	Mean	49.50	42.22	505.90
	SD	31.31	29.22	137.46
VW6	Mean	67.13	64.49	496.73
	SD	20.01	19.23	119.00
RW	Mean	49.01	46.13	558.70
	SD	9.92	8.74	122.00

- Participant 2 from VW3 commented "I wanted to stand on the skateboard."
- Participant 26 from M commented "It did not feel like walking."

It was also clear that participants were much more comfortable with RW as a navigation technique than they were with any of the other travel techniques. This attitude is illustrated by 1) participant responses to the question regarding how long it took them to get used to navigating the virtual environment, 2) our observations as to actual time in training, and 3) participant comments during the debriefing session. For example:

- Participant 20 from M commented "I never got used to the navigation!"
- Participant 24 from RW commented regarding navigation "It was easy ... I just walked around!"

Examination of the path visualizations of each condition for all the participants revealed clear differences among the participants' travel paths, collisions with objects, and view direction. M, VW3, and VW6 participants' travel paths were scattered throughout the room, whereas RW participants' travel paths were condensed in the center of the room. In addition, dwell data and spaghetti plots revealed that RW participants avoided colliding with objects in the VE more than participants in the other conditions.

Our results suggest that, for applications where problem solving and evaluation of information is important or where opportunity to train is minimal, then having a large tracked space so that the participant can walk around the virtual environment provides benefits over common virtual travel techniques.

ACKNOWLEDGMENTS

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