Evaluation of the Cognitive Effects of Travel Technique in Complex Real and Virtual Environments

Evan A. Suma, *Student Member*, *IEEE*, Samantha L. Finkelstein, Myra Reid, Sabarish V. Babu, *Member*, *IEEE*, Amy C. Ulinski, *Member*, *IEEE*, and Larry F. Hodges, *Member*, *IEEE*

Abstract—We report a series of experiments conducted to investigate the effects of travel technique on information gathering and cognition in complex virtual environments. In the first experiment, participants completed a non-branching multilevel 3D maze at their own pace using either real walking or one of two virtual travel techniques. In the second experiment, we constructed a real-world maze with branching pathways and modeled an identical virtual environment. Participants explored either the real or virtual maze for a predetermined amount of time using real walking or a virtual travel technique. Our results across experiments suggest that for complex environments requiring a large number of turns, virtual travel is an acceptable substitute for real walking if the goal of the application involves learning or reasoning based on information presented in the virtual world. However, for applications that require fast, efficient navigation or travel that closely resembles real-world behavior, real walking has advantages over common joystick-based virtual travel techniques.

Index Terms—Virtual reality, travel techniques, navigation, real walking, user study.

1 Introduction

Navigation is the most common and universal task performed when interacting with a 3D user interface [1]. While moving around in the real world usually occurs without conscious effort, those unfamiliar with computer-generated 3D environments often experience difficulty controlling their viewpoint when immersed in a virtual world. As a result, supporting natural and intuitive navigation is an important goal for the design of virtual environments. Navigating through the use of real walking is an effective way of achieving this goal, but there are a number of drawbacks associated with this approach. Therefore, it is necessary to compare this technique against other methods to identify applications where the advantages of real walking justify the trade-offs.

The overall process of navigating in a virtual environment is commonly divided into two components [1]. The motor component of navigation, known as *travel*, refers to the physical control of the user's viewpoint in a 3D environment. The cognitive component, known as *wayfinding*, involves the process of defining a path through the environment. In this paper, we investigate the travel component of navigation and describe a series of experiments which explore the effects of travel technique on users' abilities to gather and remember information in complex immersive virtual environments.

Some travel techniques attempt to replicate the energy and motions of physical locomotion. The most direct of these techniques is *real walking*, which allows the user to walk about the space in a natural manner. While this method of travel is the most similar to real-world motion, the size of the available tracking area imposes severe restrictions on the size of the virtual environment. To overcome this limitation, *walking-in-place* techniques translate the viewpoint when the user marches in stationary location, though this action does not exactly replicate the motions of real walking (e.g., [2], [3]). Physical motions of walking can also be simulated using mechanical devices such as treadmills (e.g., [4]).

In the context of this paper, we refer to *virtual travel* techniques for methods combining head tracking for orientation with some other device, such as a joystick button, to control viewpoint position. Gaze-directed steering techniques are the simplest and most common method, which translate the user forward in the direction they are looking. Pointing and torso-directed techniques have also been proposed as alternatives which decouple the user's view from the direction of travel [1]. These techniques all have the advantage of allowing arbitrarily large virtual environments when using a small physical workspace, but generally require the user to manipulate an additional interface device.

Recent advances in wide-area tracking technology enable us to track a user's position and orientation throughout spaces that are much larger than the 1.5-3 meter diameter spaces normally imposed by electromagnetic tracking devices [5]. While locomotion achieved entirely through real walking is now practical for certain applications, wide-area tracking systems such as the Intersense IS-900 or the

- *E.A. Suma and S.L. Finkelstein are with the Department of Computer Science, University of North Carolina at Charlotte, 404 Woodward Hall, 9201 University City Blvd, Charlotte, NC 28223. E-mail: {easuma, sfinkel1}@uncc.edu.*
- *M. Reid is with the Department of Psychology, University of North Carolina at Charlotte, 404 Woodward Hall, 9201 University City Blvd, Charlotte, NC 28223. E-mail: mreid19@uncc.edu.*
- *S.V. Babu, A.C. Ulinski, and L.F. Hodges are with the School of Computing, Clemson University, McAdams Hall, Clemson, SC 29634. E-mail: {sbabu, aulinsk, lfh}@clemson.edu.*

Manuscript received 29 Mar. 2009; revised 11 July 2009; accepted 29 July 2009; published online 7 Aug. 2009.
Recommended for acceptance by A. Steed.
For information on obtaining reprints of this article, please send e-mail to: tvcg@computer.org, and reference IEEECS Log Number TVCG-2009-03-0069.
Digital Object Identifier no. 10.1109/TVCG.2009.93.

3rdTech Hiball are more expensive than limited-area trackers, and the cost of these systems increases as the tracker workspace area is expanded. Additionally, these systems require a large amount of empty space to provide an area for the user to freely walk around, which could be prohibitive for settings with limited space. Nevertheless, this technology enables us to measure the relative efficacy of real walking in an immersive virtual environment as opposed to virtual travel techniques.

Evaluation of different methods of travel in virtual environments is important to understand the applications which justify the cost and space trade-offs of real walking. Given the fundamental importance of navigation in 3D environments, the implications of this work are significant for a variety of domains. The need for navigation methods to support specialized military applications, such as infantry training and tactics, has led to the development of several novel locomotion control methods (e.g., [4], [6]). In particular, we are concerned with studying the cognitive effects of travel, such as information gathering and learning. These criteria are especially important for applications such as education, architecture, industrial design, and visualization, where understanding the information in the environment is an essential goal of the system.

Previous work has shown that real walking is easier and supports a greater sense of presence than both walking-in-place and joystick-based virtual travel techniques [7]. Chance et al. found that real walking enabled participants to indicate the direction to unseen target objects from a terminal location in a maze better than virtual travel techniques [8]. They also reported that participants that used real walking experienced less motion sickness and scored higher in mental map and basic navigation tests. In a study that attempted to characterize task behavior and performance, Whitton et al. found that the motions when using walking-in-place or virtual travel do not correlate well with real walking motions [9]. Additionally, Ruddle and Lessels found that real walking allowed near-perfect performance on a navigational search task, whereas gaze-directed travel resulted in less than 50 percent of trials performed perfectly [10], [11].

Differences between virtual travel techniques have also been noted; Bowman et al. have shown that pointing techniques are advantageous to gaze-directed steering techniques when attempting to travel a relative distance and direction from a reference point [12]. They also reported that motion techniques that instantly teleport users to new locations are correlated with increased user disorientation. However, in an information gathering experiment, no significant differences were found between gaze-directed, pointing, and torso-directed virtual travel techniques for the amount of information recalled by participants [13]. Additionally, Vidal et. al. compared the ability to memorize a complex 3D maze when using different reference frames for navigation, and found that participants were better able to recognize complex corridors when navigation was restricted to yaw rotations, keeping the viewer's virtual body upright, as opposed to using yaw, pitch, and roll rotations together [14].

Studies have also previously examined travel and cognition in virtual environments. Jeong et al. found that participants who explored a real-world environment gathered more information than those who explored a virtual world [15]. They attribute this difference to the cognitive load associated with exploration of the virtual world using a virtual travel technique. In a study that investigated travel technique in particular, Zanbaka et al. found that real walking allowed significantly higher scores than gaze-directed steering on cognitive measures involving understanding and application as well as the higher mental processes [16]. It is important to note that this experiment evaluated exploratory travel in a single small room which did not require complex maneuvers to navigate. However, previous research has found that the complexity of an environment has a profound impact on navigation tasks [13], [17]. It has not been investigated whether the increased cognitive load required by maneuvering around complex turns influences the benefits of real walking over virtual travel techniques.

We conducted a series of studies to explore the cognitive benefits of real walking in complex environments. In this context, complexity refers to the number of turns required to navigate through the structure of the environment, and is unrelated to the amount of visual detail. We chose two investigate environments with two different types of pathways: *branching* (with multiple navigational decision points) and *non-branching* (with no decision points). Previous studies have used the number of navigational decision points in defining the complexity of an environment and have shown these points to be a distinguishing factor for memory retention of landmarks [18], [19]. In general, it has been shown that decision making is a critical component for learning in a virtual environment [20].

In Section 2, we describe the hardware and software framework used to conduct our experiments. Next, in Section 3, we describe the results of our first experiment, which required navigation through a complex virtual environment with a non-branching path. Though we hypothesized that real walking would allow superior performance over two virtual travel techniques on tests of memory about the environment, no significant differences were found on these measures. Preliminary results from this study were previously published at the IEEE Symposium on 3D User Interfaces in 2007 [21]. In Section 4, we report a new experiment which required navigation through a complex maze with branching paths in either the real world or a virtual environment using two different methods of travel. This experiment was conducted to identify explanations for the lack of significant differences in the first study and to further investigate the cognitive effects of travel technique on measures of memory, understanding and reasoning, and similarity of movement to real-world behavior. In Section 5, we discuss the implications of our results across both experiments and conclude the paper.

2 Experiment Framework

To compare the differences between real walking and common virtual travel methods, we developed a framework which could be used to run experiments using different travel techniques. We utilized this framework to conduct all the studies described in this paper.

(a) (b)

Fig. 1. (a) When using the real walking technique, participants can naturally walk around about the space. (b) When using a virtual travel technique, physical movement is restricted and travel is accomplished using a handheld device.

2.1 Equipment

For display of virtual environments, we used the Virtual Research VR1280 head-mounted display, which provides stereoscopic graphics with a 60-degree diagonal field-of-view and stereo sound. Each eye was rendered at a resolution of 1280×1024 at 60 Hz. We ran all experiments using a Dell Pentium 4 3.0 GHz PC running Windows XP with 1 GB of RAM. For the initial experiments, we were using an NVIDIA Geforce 6800 graphics card—this was upgraded for the final experiment to a Geforce 7950 GTX.

Head position and orientation were captured using the 3rdTech Hiball 3100 wide-area tracking system. This device uses optical tracking to provide highly accurate measurements with six degrees of freedom. The total amount of area tracked by our system was $14' \times 16'$. The cables attached to the head-mounted display were mounted to the ceiling, and an assistant was present to guide the cables to prevent tangling while the participant was walking around.

2.2 Software

Virtual environments were created using the 3D GameStudio A6 engine, which provided environment modeling tools, 3D rendering, sound, event scripting, and collision detection. Add-on modules were written in C++ to integrate the engine with the Virtual Reality Perepheral Network, which facilitated network communication with the tracking system [22]. Graphics were rendered in software at approximately 55-60 frames per second; 32-bit spatialized 3D sound was provided using a sampling rate of 44100 Hz. Collision detection prevented the virtual viewpoint from traveling through walls, and an audio buzzer was played in the event of a collision to alert the user.

2.3 Experimental Setup

Participants that used the real walking technique were allowed to naturally walk throughout the tracking space, with the position and orientation of their viewpoint mapped directly from the tracker (Fig. 1a). Participants that used virtual travel techniques were restricted in their physical movements by a $4' \times 4'$ enclosure constructed from PVC pipe (Fig. 1b). This enclosure forced participants to use the virtual travel technique for locomotion while allowing limited physical movement for the purposes of maneuvering. To trigger movement and adjust velocity, one or two handheld devices were used (see the sections on each individual experiment for details). When using virtual travel, a vertical bar was presented on the right side of the HMD screen. This was done to provide visual feedback of the currently selected movement speed in order to reduce trial and error when adjusting velocity.

3 Experiment 1: Multilevel 3D Maze

For this experiment, we modeled a virtual environment that was larger and more complex in terms of navigation and structure than was done in previous studies of travel technique and cognition (e.g., [16]). We used this environment to conduct a user study with three different locomotion methods to determine if real walking provides benefits over virtual travel techniques when faced with a difficult navigation task.

3.1 Virtual Environment

The experiment environment was designed as a 3D maze with two levels, allowing us to double the area of the environment (448 sq. feet) while still fitting within our physical limitations (Fig. 2). The dimensions of the environment were precisely designed to fit our $14' \times 16'$ tracking area, leaving 6-inch borders around the perimeter of the area to avoid collisions with the physical environment. Fig. 3 shows an example screenshot of the virtual environment.

The path through the maze was linear; there were no branching hallways. At the end of the path on the first floor, the participant reached a dead end with an elevator which led to the second floor. Upon reaching the end of the path on the second floor, the simulation recorded the completion time of the maze. A collection of 18 objects was placed

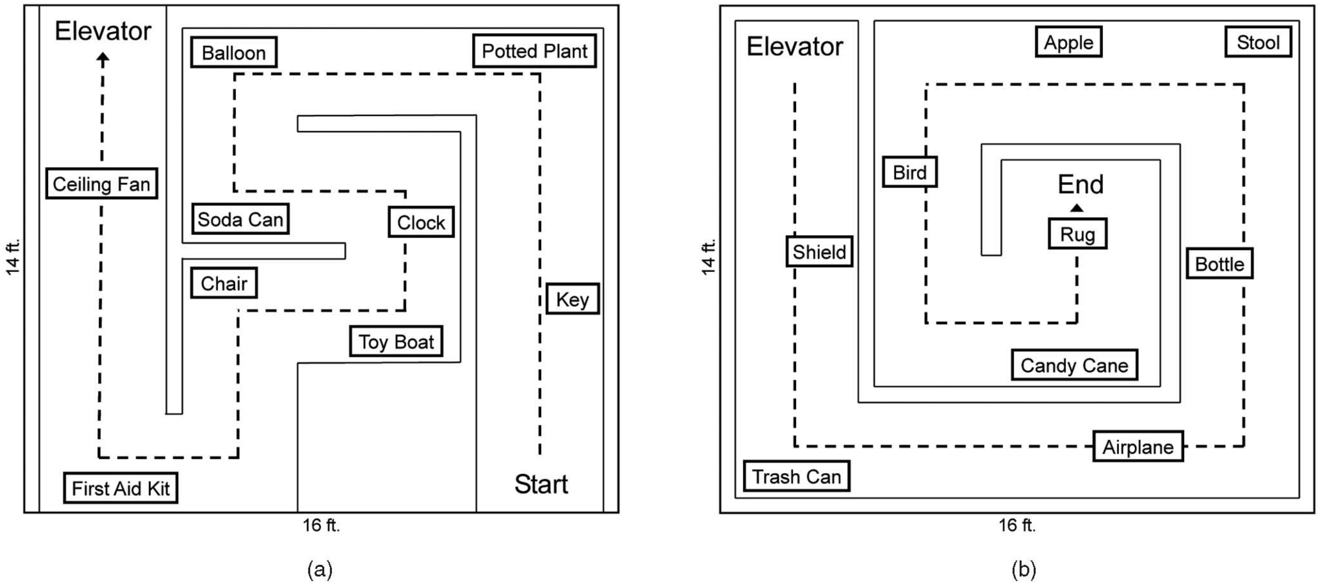

Fig. 2. (a) Participants navigated through the first floor of the environment until reaching an elevator, which took them to the second floor. (b) After following the path on the second floor, participants reached the end of the maze.

throughout the environment, including many everyday objects such as a clock, a potted plant, and a toy airplane. Objects were divided evenly across three height ranges:

- **Low:** Objects were placed on the floor or at the base of the wall.
- **Medium:** Objects were placed on the wall approximately halfway between the floor and ceiling.
- **High:** Objects were placed on the ceiling or on the wall adjacent to the ceiling.

3.2 Experimental Design

The study used a between-subjects design with participants randomly assigned to one of the following three conditions:

1. **Real Walking (RW):** Participants were allowed to naturally walk around the area with their physical position and orientation mapped directly to their position and orientation in the virtual environment.
2. **Moving-Where-Looking (MWL):** Participants used a handheld trigger to move forward in the direction determined by their gaze.
3. **Moving-Where-Pointing (MWP):** Participants used the trigger to move forward in the direction determined by a tracker mounted on the handheld device.

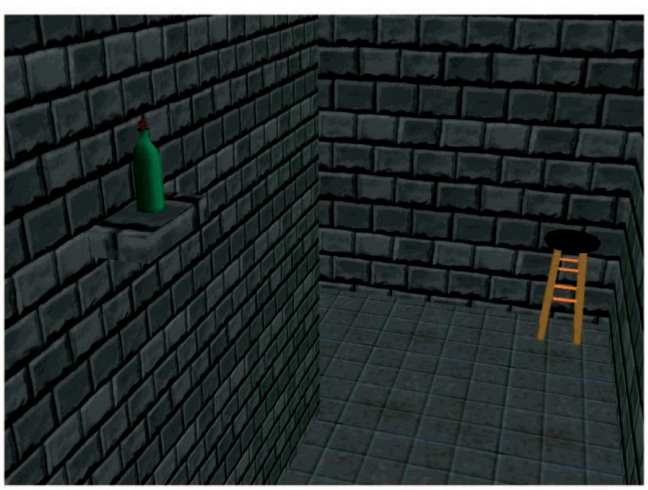

Fig. 3. A screenshot of the virtual environment used in Experiment 1.

For the virtual travel conditions (MWL and MWP), travel was accomplished using a handheld Hiball joystick device held in the dominant hand. When the participant pressed the trigger button, the view in the virtual environment was translated forward in the appropriate direction. Additinally, in the MWP condition only, an arrow was rendered on screen at the position and orientation of the user's hand. Since participants could move at different speeds in the real walking condition, it was necessary to provide velocity control in the virtual travel conditions. The handheld tracker device did not support additional controls to adjust velocity, so we added a PC Ally Airstick in the nondominant hand. The participant manipulated a thumb joystick on this device which acted as a throttle, which was controllable in a range of 0-3 meters per second. We observed that most participants would set the velocity to a comfortable level somewhere between these two extremes at the beginning of each experiment and then ignore use of the speed control device for the rest of their exploration.

We hypothesized that participants using the real walking technique would exhibit superior performance over virtual travel techniques in tests about the structure and contents of the environment. Additionally, we expected real walking to facilitate faster completion of the maze with fewer collisions with the walls of the environment.

3.3 Measures

3.3.1 *Simulator Sickness*

Simulator sickness was measured using the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [23]. The questionnaire was administered immediately before and after the virtual reality session.

3.3.2 Spatial Ability

Participants were pre-tested for spatial ability using the Guilford-Zimmerman Aptitude Survey Part 5: Spatial Orientation [24]. The test consisted of 60 questions relating to spatial position and orientation with a maximum time limit of 10 minutes.

3.3.3 Object Recall

Participants were asked to list as many objects as they could remember from the environment on a sheet of paper. The number of correct objects listed was summed to provide a score from 0 to 18, with higher numbers corresponding to better performance. Participants were allowed up to 5 minutes to complete this test.

3.3.4 Object Recognition

Participants were given a list of 36 objects, consisting of the 18 objects in the environment and 18 objects not in the environment. The order of objects was randomized. The participant was instructed to mark the object with a "Y" if they thought the object was present in the environment or an "N" if they thought the object was not present. The number of false positives was subtracted from the number of correct true positives, which yielded a final score between 0 and 18, with higher numbers corresponding to better performance. Participants were allowed up to 8 minutes to complete this test.

3.3.5 Sketch Maps

Participants were given two blank sheets of paper and instructed to sketch two top-down maps of the environment (one for each floor). They were allowed up to 5 minutes to complete this test.

Maps were independently evaluated by three graders who were blind to the participants' condition. Each map was assigned a goodness score on a scale of 1 (poor) to 5 (excellent), similar to what was done in [16] and [25]. Graders were instructed to evaluate the maps based upon a subjective comparison of the maze structure with a correct map of the environment. The visual quality of the map and the drawing ability of the subject were ignored.

3.3.6 Object Placement

Participants were given two complete maps of the environment (one for each floor) and a list of all objects present in the environment. The list of objects was numbered sequentially and randomly ordered. The participants were instructed to write the number of the object on the map at the location they thought it was present in the environment. They were not required to mark every object on the map. A consistent grader scored the maps to determine the number of correctly placed objects, but as locations may be inexact, the grader was required to use judgment in certain cases. The number of objects correctly placed on the map was summed to provide a score ranging from 0 to 18, with higher numbers corresponding to better performance. Participants were allowed up to 10 minutes to complete this test.

3.3.7 Experiment Data

The system automatically logged the time each participant took to complete the maze as well as the number of collisions with the walls of the environment. The participant's position and orientation at each frame were also recorded by the system.

3.4 Experiment Procedure

The pre-experiment, experiment, and post-experiment sessions took each participant approximately one hour to complete.

3.4.1 Pre-Experiment

The participant was given an information sheet which listed the procedure and tests used in the experiment. Minimal detail was given so that the participant knew testing would involve remembering both map and object information from a virtual environment. However, the experiment hypotheses were not disclosed. After signing the informed consent form, the participant was given the opportunity to ask questions. The participant then completed the spatial ability test followed by simulator sickness pre-test immediately before the experiment session.

3.4.2 Experiment Session

The participant was led to the experiment area of the laboratory and introduced to the equipment. The experimenter gave instructions to explore the maze from start to finish and informed the participant that several post-tests on the layout of the maze and objects in the environment would be administered after completing the maze. After allowing the participant the opportunity to ask questions, the experimenter fitted the participant with the head-mounted display and handheld controllers (for the MWL and MWP conditions).

Before entering the experiment environment, the participant was given a training session in which the controls and equipment were explained. The participant was then immersed in a training environment for approximately one minute and was given a simple movement task to complete, which required moving back and forth between different objects in a room. Finally, the participant was given another opportunity to ask questions.

When the participant was ready to begin, the experiment environment was loaded and the participant was instructed to explore the maze until reaching the end, paying attention to the environment during the exploration. Each participant was instructed to complete the maze at their own pace and was given no time limit. The experiment session was concluded when the end of the maze was reached.

3.4.3 Post-Experiment

Immediately after completing the maze, the participant filled out the post-test for simulator sickness. Subsequently, four post-tests were completed in the following order:

1. object recall,
2. object recognition,
3. sketch maps, and
4. object placement.

After completing all tests, the participant was debriefed and given a final opportunity to ask questions or provide comments.

3.4.4 Participant Information

Participants were recruited from computer science courses, fliers, and word-of-mouth, and were required to have normal or corrected-to-normal vision and be able to communicate in written English.

Initially, a total of 49 participants completed this experiment with 17 in the RW condition, 17 in the MWL condition, and 15 in the MWP condition (2 participants were eliminated due to incomplete data and technical errors in data collection). We noticed that 20 participants from this initial study scored very low (less than 5) on the spatial ability test. Additionally, the distribution of these scores was highly uneven across the conditions with 1 in the RW condition, 9 in the MWL condition, and 10 in the MWP condition. The results from this initial study are reported in [21].

To correct the problems that we observed in spatial ability, we performed a follow up with a second round of participants. Since the spatial ability distribution indicates that one group had an advantage over another in spatial orientation, this confounds the interpretation of our results, especially since the group with higher spatial ability (RW condition) performed better on several measures. We excluded the participants with very low scores on the spatial ability test from our data set and replaced them with new participants. A total of 22 participants were added to the study and were distributed as follows: 1 in the RW condition; 9 in the MWL condition; and 12 in the MWP condition. A score greater than 5 on the spatial ability pre-test was required as an inclusion criterion. During the experiment, only two participants did not meet this inclusion criterion and were replaced. Thus, the corrected results reported in this paper include a total of 51 participants with 17 in each condition.

3.5 Results

Unless otherwise noted, the results for each test were treated with a a one-way between-subjects analysis of variance (ANOVA) across all conditions with a significance level of $\alpha = .05$. Table 1 shows the mean results from this experiment.

TABLE 1
Mean Results from Experiment 1

	RW	MWL	MWP
Object Recall	7.94 (44%)	8.12 (45%)	7.35 (41%)
Object Recognition	9.50 (53%)	9.88 (55%)	8.81 (49%)
Object Placement	3.94 (22%)	3.29 (18%)	2.71 (15%)
Sketch Maps (1-5)	2.95	2.79	2.37
Time (sec.)*	104.80	134.58	184.51
Collisions*	.24	.82	2.35

**test was significant at α = .05 level*

3.5.1 Simulator Sickness

During preliminary analysis, we identified one outlier in the MWP condition who reported very high SSQ scores both prior to and after exposure to the virtual environment. This indicates that the participant was feeling ill, and so we eliminated these scores from this analysis. A 2×3 mixed ANOVA was performed, testing the within-subjects effect of SSQ score before and after the experiment session and the between-subjects effect of travel technique. The analysis revealed a nonsignificant interaction, $F(2,47) = 0.14$, $p = .871$. The main effect for SSQ score was not significant, $F(1,47) = 1.27, p = .265$, nor was the main effect for travel technique, $F(2,47) = 0.87, p = .427$. These results indicate reported simulator sickness did not significantly change from before ($M = 11.74, SD = 12.51$) to after exposure to the virtual environment ($M = 14.21, SD = 14.08$). Additionally, the amount of simulator sickness did not vary across the different travel techniques.

3.5.2 Spatial Ability

The ANOVA was not significant, $F(2,48) = 1.10, p = .342$. These results indicate that the spatial ability pre-test scores were even across the conditions. Thus, we can draw more confident conclusions from our final results than we could from our first round of participants.

3.5.3 Post-Tests

No significant differences were found between travel techniques for object recall, $F(2,48) = 0.43, p = .651$, or object recognition, $F(2,46) = 0.40, p = .674$. These results indicate that travel technique does not appear to influence the ability to recall or recognize information from a virtual environment. Similarly, no significant differences were found between travel techniques for sketch maps, $F(2,48) = 2.02, p = .144$, or object placement, $F(2,48) = 1.21, p = .308$. These results indicate that travel technique did not positively or negatively affect the ability to sketch the maze layout or label object locations.

3.5.4 Experimental Data

During the experiment session, two participants (one in the RW condition and one in the MWL condition) did not follow a direct path through the maze. Instead, they turned around and walked back and forth through the maze multiple times. Since their results do not accurately reflect the amount of time needed to complete the maze, we eliminated these scores from our analysis of completion times. The ANOVA was significant, $F(2,46) = 12.97$, $p = .001$. Post hoc analysis with the Tukey HSD test revealed significant differences between the MWP condition and the RW ($p = .001$) and MWL conditions, $p = .008$. The RW and MWL conditions were not significantly different, $p = .165$. These results indicate that the real walking and gaze-directed techniques allow a participant to complete a task involving travel in the environment more efficiently than the pointing technique.

The results for the number of collisions were significant, $F(2,48) = 8.75, p = .001$. Posthoc analysis with the Tukey HSD test revealed significant differences between the MWP condition and the RW ($p = .001$) and MWL conditions, $p = .014$. The RW and MWL conditions were not significantly different, $p = .503$. These results indicate that the real walking and gaze-directed techniques allow a participant to explore the environment with fewer collisions with the virtual geometry than the pointing technique.

3.6 Discussion

Participants that used the real walking and the moving-where-looking techniques did no worse than those using the moving-where-pointing technique on any of our post-tests, but completed the environment in less time and with fewer collisions with the environment. This suggests that in complex 3D environments where exploration occurs at one's own pace, the moving-where-pointing technique provides a less efficient method of travel. Additionally, the real walking and moving-where-looking techniques reduced the number of collisions with virtual walls of the environment, indicating that these technique could be beneficial for applications where it is important to maintain a high degree of immersion. However, it is important to note that the moving-where-pointing technique is more complicated than the other two techniques and may take greater amounts of training to become proficient. Thus, these results may only be applicable to situations where we can assume users have had only minimal amounts of training.

We did not observe any statistically significant differences for recall or recognition of objects, sketching of maps, or object placement within the environment, which we initially expected to find based on previous studies of smaller environments which were more simple to navigate. It is possible that the increased cognitive load required to navigate complex virtual environments inhibits learning regardless of travel technique. However, another possible explanation lies in observing that participants using virtual travel conditions took more time to complete the maze. Though navigation appeared more difficult, these participants had greater exposure to the contents of the environment. We attempted to address these questions, and others, in Experiment 2.

4 Experiment 2: Real versus Virtual Maze

In light of the lack of significant differences in Experiment 1, we conducted a new experiment to further investigate the relationship between travel technique and cognition. We constructed a complex maze with branching pathways in our tracking area which allowed us to compare navigation in the real world to an identical virtual environment using either real walking or virtual travel. The real-world condition provides a baseline comparison to gauge whether nonsignificant results are due to overall task difficulty or conditions specific to the virtual environment. Additionally, this experiment provides us the opportunity to compare movement statistics and user experience data to exploration in the real world. Real walking is usually assumed to be more realistic than virtual travel techniques, but not much data exist to evaluate the degree to which different travel techniques cause navigation to deviate from real-world behavior.

In contrast to Experiment 1, we designed the environments with branching paths and ensured that all participants explored the environment for the same amount of time, resulting in an equal amount of exposure. Also, previous researchers have found that the addition of multisensory input such as audio to a virtual environment can increase sense of presence and memory of the environment [26]. Thus, we designed this study to incorporate both visual and auditory information. In addition to tests of memory, we also included measures of cognition related to knowledge, understanding, and reasoning.

4.1 Experiment Environments

4.1.1 Maze Design

The maze was designed to be an enclosed environment with no exit. Columns were placed throughout the space as barriers, creating a complex space requiring the user to navigate around obstacles during exploration of the $14' \times 16'$ rectangular tracking area.

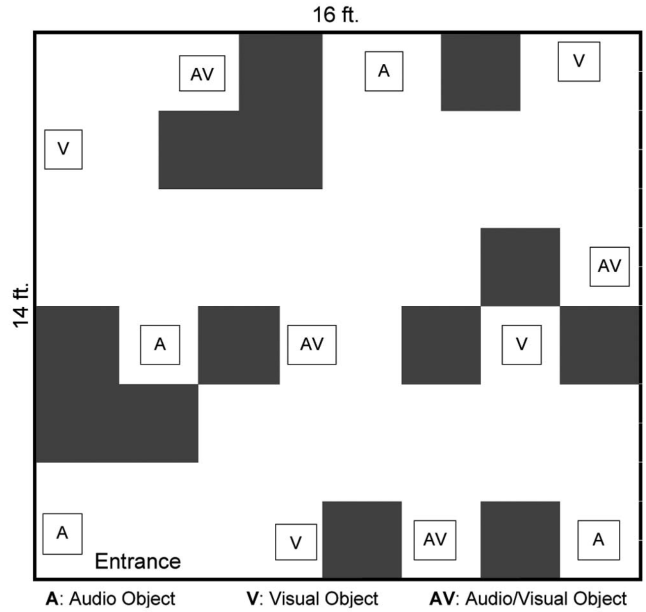

Fig. 4. A map of the maze layout used to create the real world and virtual environment used in Experiment 2. Dark areas represent barriers that the user had to navigate around. Each box denotes the location of an object.

A total of 12 objects were placed throughout the environment, divided evenly between high and low-height locations. High objects were located at approximate eye level when standing; low objects were placed close to the ground. We divided the objects evenly among three types:

- **Visual (V):** Pictures fastened to a wall or column (e.g., a palm tree),
- **Audio (A):** Sounds located at fixed positions in the environment (e.g., birds chirping),
- **Audio/Visual (AV):** Pictures with a conceptually matched sound in the same location (e.g., a birthday cake with voices yelling “surprise”).

Fig. 4 shows the layout of the maze and the locations of objects.

4.1.2 Maze Construction

For the real-world maze, a frame was constructed around the boundaries of the tracking area out of PVC pipe. Blue tarps were stretched around this frame to create walls around the area, forming the enclosed room. Barriers were created by stacking $2' \times 2'$ cardboard boxes to form a $2' \times 2' \times 6'$ tower which was weighted at the bottom. Fig. 5 shows a participant exploring the maze.

Spatialized 3D sound was provided using high-quality stereo headphones. We chose to use headphones in the real world in order to closely match the audio experience in the virtual environment and to reduce background noise. The tracker was mounted to the top of the headphone band to provide the view angle as well as to record the participant’s movements for comparison to the virtual environment conditions. The cables for the headphones and tracker were tethered to the ceiling in the center of the environment, which reduced the tangling of cables. The radius for triggering a sound was approximately 2.5 feet, but the volume was made

Fig. 5. A picture of a participant exploring the real-world maze used in Experiment 2.

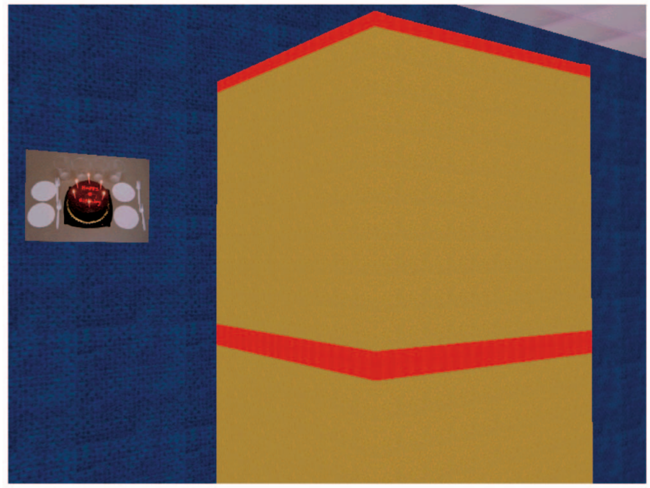

Fig. 6. A screenshot of the virtual environment used in Experiment 2.

to fade in gradually to provide a realistic effect and to prevent sounds from interfering with one another.

The dimensions of the real-world maze were measured precisely so that an identical virtual environment could be modeled. The virtual environment contained the same objects and was textured using photographs of the real-world environment. It is important to note that a simple uniform lighting model was used, and this may not have captured all the subtleties in illumination that were present in the real-world maze. Fig. 6 shows a screenshot of the virtual environment.

4.2 Experimental Design

The experiment used a between-subjects design with participants randomly assigned to one of three conditions:

- **Real World (R):** Participants explored the real-world maze.
- **Virtual Environment—Real Walking (VRW):** Participants explored the virtual maze by naturally walking, with their physical position and orientation mapped directly to their position and orientation in the virtual environment.
- **Virtual Environment—Virtual Travel (VVT):** Participants explored the virtual maze using the gaze-directed virtual travel technique. Movement and velocity were controlled using a PC Ally Airstick held in the dominant hand, with adjustable speed in the range of 0-3 meters per second.

Based on previous research [13], combined with the results of Experiment 1, we did not expect differences between gaze-directed travel and other virtual techniques on cognitive measures. As a result, we chose to evaluate real walking against gaze-directed travel, and did not include the pointing technique in this study.

4.3 Measures

4.3.1 Pre-Tests

Participants were given the same pre-tests for spatial ability and simulator sickness as in Experiment 1. They were also given a demographic questionnaire to assess handedness, computer usage, and video game experience.

4.3.2 Object Recall

Participants were instructed to list as many objects as possible from the environment, including both pictures and sounds. The number of objects correctly remembered was summed to provide a score from 0 to 12. For objects with both an audio and visual component, participants received half credit for remembering only one component without the other.

4.3.3 Cognition Questionnaire

Participants were given a three-part questionnaire to assess cognition, similar to what was done in [16]. The questions were based on Bloom's Taxonomy of the Cognitive Domain, which divides human cognition into six categories: Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation [27]. Crooks further condenses these components into three major categories [28]. We developed a set of 24 questions about the environment, each of which correspond to one of these three categories:

- **Knowledge:** recall of specific information and details. *Example question:* How many baby birds were in the nest?
- **Understanding and Application:** understanding and interpretation of information, problem solving, and application of concepts to new situations. *Example question:* How old is the person who has the cake? How did you arrive at your answer?
- **Higher Mental Processes:** analysis of facts and inferences, integration of learning from different areas, creative thinking, and evaluation and judgment of information. *Example question:* Given what you observed in the maze, name a place that someone who made this environment might go on vacation.

The questions on the test were as balanced as possible with regard to object type (A, V, or AV), location in the maze, height level, and theme. The test was administered separately in three parts. The Higher Mental Processes portion was administered first, followed by Understanding and Application, and finally, Knowledge. Since questions in the Knowledge category had more to do with details about the environment, this order was important in order to reduce the possibility of these questions being used as additional information to answer questions from the other two categories.

Correct answers for each question were awarded one point. On some questions, answers could be partially or approximately correct; in this case, a half-point was awarded. The points were summed to provide a score between 0 and 8 for each category.

4.3.4 Map Placement

Participants were given a map of the environment with empty boxes corresponding to object locations and a list of all objects in the environment. The list was presented on a computer. Rather than describe the objects in words, which could lead to problems in interpretation, the picture for each object was displayed on screen and/or the sound could be played by clicking on the object. Each object was coded with a number, and the participant was instructed to write the number on the map in the box where they thought the object was located. Additionally, the participant was instructed to write either an H or L next to each object placed on the map, depending on the object's height level. Answers on this test were not forced; participants could skip objects they didn't see or couldn't remember. The number of objects correctly placed was summed to provide a score between 0 and 12.

4.3.5 Experiment Data

Tracker data during the experiment session were recorded for offline analysis. From this data, we calculated the following statistics:

1. total amount of left and right head turn in degrees,
2. total horizontal distance moved in meters,
3. total vertical distance moved in meters, and
4. number of collisions with the geometry of the environment.

4.4 Experimental Procedure

The pre-experiment, experiment, and post-experiment sessions took approximately 45-60 minutes to complete.

4.4.1 Pre-Experiment

The participant was given an information sheet which listed the procedure and tests used in the experiment. Minimal detail was given so that the participant knew testing would involve remembering object details and locations. However, the experiment hypotheses were not disclosed. After signing the informed consent form, the participant was given the opportunity to ask questions. The participant then completed the demographic questionnaire, the spatial ability test, and the simulator sickness pre-test immediately before the experiment session.

4.4.2 Experiment

The experiment session and instructions were first explained to the participant, who was given another opportunity to ask questions about the experiment. The participant was told to explore either the real or virtual maze for five minutes and was instructed to attempt to learn about the layout and contents of the environment during their exploration.

In the R condition, the participant was fitted with the headphones and tracker, then allowed to enter the maze. The entrance was closed, leaving the participant alone within the maze. The participant's movements were monitored by displaying the virtual maze on the screen, rendered from the participant's point of view. After five minutes, the experiment session ended.

For the virtual environment conditions, the participant was fitted with the head-mounted display. In the VVT condition only, the participant climbed into the PVC enclosure and was given the joystick and shown how to control movement and speed in the virtual environment. For both conditions, the participant was then given the same immersive training task as Experiment 1. This training task lasted approximately one minute, after which the participant was moved to a set starting location and began exploring the maze.

4.4.3 Post-Experiment

Immediately after the experiment session, the participant filled out the post-test for simulator sickness. The participant then completed questionnaires in the following order: 1) object recall, 2) cognition, and 3) map placement. After completing the questionnaires, the participant was debriefed and given an opportunity to ask questions and provide verbal feedback.

4.4.4 Participant Information

Participants were recruited primarily from computer science and psychology courses, fliers, and word-of-mouth, and were required to have normal or corrected-to-normal vision and be able to communicate in written English. A total of 90 people participated in the study (46 male, 44 female) with 30 participants in each condition. The mean age of participants was 22.21 ($SD = 6.98$).

4.5 Results

Unless otherwise noted, the results for each test were treated with a a one-way between-subjects ANOVA across all conditions with a significance level of $\alpha = .05$.

4.5.1 Simulator Sickness

A 2×3 mixed ANOVA was performed, testing the within-subjects effect of SSQ score before and after the experiment session and the between-subjects effect of experiment condition. The analysis revealed a significant interaction, $F(2,87) = 9.78, p < .001$. The main effect for time was not significant $F(1,87) = 0.59, p = .446$, nor was the main effect for experiment condition, $F(2,87) = 1.74, p = .183$. These results indicate that simulator sickness varied from before to after instruction differently depending on the experimental condition. Fig. 7 shows a profile plot for this test.

Paired sample t-tests were conducted to determine individual differences for each condition:

- R Condition: $t(29) = 3.93, p < .001$,
- VRW Condition: $t(29) = 2.69, p = .012$,
- VVT Condition: $t(29) = 0.46, p = .657$.

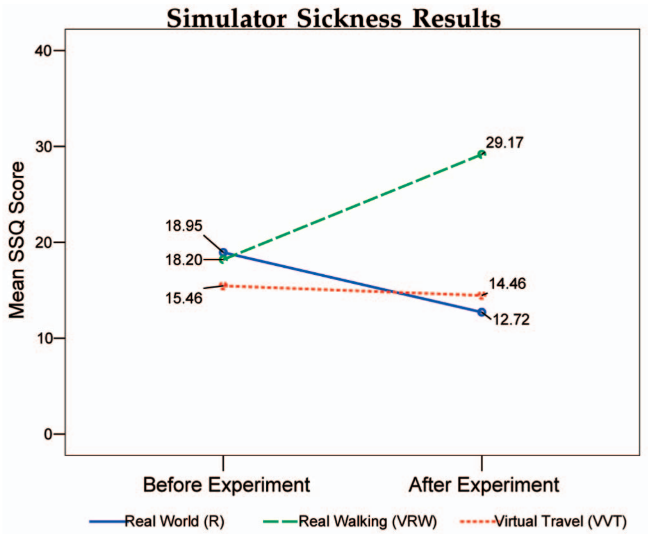

Fig. 7. Mean SSQ results for Experiment 2. SSQ scores in the real walking condition were greater after the experiment, but decreased in the real world and virtual travel conditions.

The most prominent result is the increase in simulator sickness in the VRW condition from before to after exposure to the environment, which was highly significant. The VVT condition dropped slightly, but this difference was not significant. Simulator sickness in the R condition, however, dropped significantly. The testing effect is one possible explanation for the lower scores, where the retesting of the same questionnaire biases the participants toward lower scores. This explanation seems likely since we have no other reason to believe participants in the R condition would have experienced any difference in symptons from before to after the experiment. Additionally, testing effects for this questionnaire have been noted in previous work [29]. Given the trend toward lower post-test scores in the other conditions, this makes the rise in simulator sickness in the VRW condition even more alarming.

4.5.2 Spatial Ability

During preliminary analysis of spatial ability scores, we eliminated one extreme outlier from the data set. The ANOVA was not significant, $F(2, 86) = 1.07, p = .346$. These results indicate that the spatial abilities of the participants were evenly balanced across the conditions.

4.5.3 Object Recall

The results were significant, $F(2, 87) = 23.46, p < .001$. Post-hoc analysis with the Tukey HSD test revealed that participants in the R condition $(M = 8.93, SD = 0.19)$ received higher scores than participants in the VRW condition $(M = 6.40, SD = 1.40), p < .001$, and the VVT condition $(M = 6.43, SD = 1.66), p < .001$. The VRW and VVT conditions were not significantly different, $p = .898$. These results indicate that participants in the real-world condition were able to remember more objects than in the virtual environment conditions. However, travel technique in a virtual environment does not appear to influence this factor.

4.5.4 Cognition Questionnaire

Univariate ANOVAs were conducted for each portion of the quesitonnaire. The results were significant for Knowledge, $F(2, 87) = 3.77, p = .027$, Understanding and Application, $F(2, 87) = 7.70, p = .001$, and Higher Mental Processes, $F(2, 87) = 11.60, p < .001$. These results indicate that the experimental condition systematically influenced the individual results for all three portions of the questionnaire.

TABLE 2
Cognition Questionnaire Post Hoc Test

	K[1]	U&A[2]	HMP[3]
R - VRW	.161	.003*	.001*
R - VVT	.023*	.003*	.001*
VVT - VRW	.680	.996	.778

[1]Knowledge, [2]Understanding and Application, [3]Higher Mental Processes

$*$ *test was significant at* $\alpha = .05$ *level*

To examine the individual differences between conditions for each of the three measures, we conducted post hoc multiple comparisons using the Tukey HSD test. Table 2 shows the significance values of these tests. The results indicate that the participants in the real-world condition had superior cognition scores for all three measures compared to the virtual environment conditions. Additionally, travel technique in the virtual environment conditions did not appear to influence performance on any of the cognition measures. Fig. 8 shows the mean scores across conditions for each of the three cognition measures.

4.5.5 Map Placement

The results were significant, $F(2, 87) = 33.24, p < .001$. Post-hoc analysis with the Tukey HSD test revealed that participants in the R condition $(M = 9.93, SD = 2.61)$ received higher scores than participants in the VRW condition $(M = 4.27, SD = 3.22), p < .001$, and the VVT condition $(M = 4.20, SD = 3{,}49), p < .001$. The VRW and VVT conditions were not significantly different, $p = .860$. These results indicate that participants in the real-world condition were able to correctly place more objects on a map than in the virtual environment conditions. Travel technique in a virtual environment does not appear to influence this factor.

4.5.6 Collisions

We restricted the analysis for collisions to the VRW and VVT conditions only, since it was not sensible to calculate collisions with virtual geometry in the R condition. An independent samples t-test was performed, which was significant, $t(58) = 2.37, p = .021$. Participants in the VRW condition experienced fewer collisions $(M = 3.50, SD = 3.32)$ than participants in the VVT condition $(M = 5.73, SD = 3.97)$. These results indicate that it is more difficult to avoid collisions with the virtual geometry when using a virtual travel technique.

4.5.7 Distance Covered

ANOVAs were performed on both horizontal and vertical distance covered. The results were significant for horizontal distance, $F(2, 87) = 34.14, p < .001$, and vertical distance, $F(2, 87) = 28.76, p < .001$.

Post hoc analysis with the Tukey HSD test revealed that participants in the R condition $(M = 98.35, SD = 20.82)$ covered more horizontal distance than participants in the

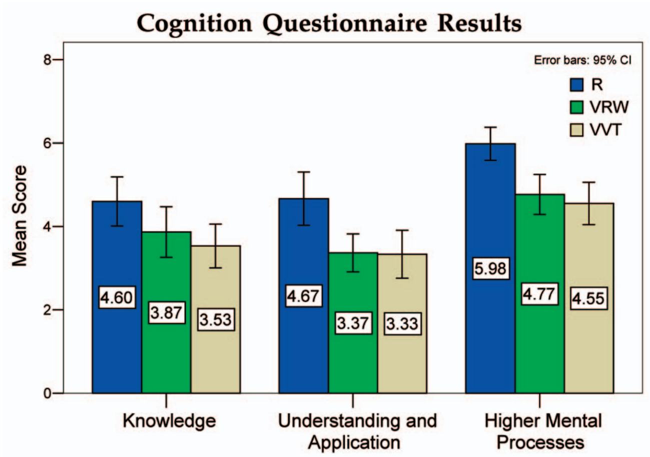

Fig. 8. Mean results for the three portions of the cognition questionnaire in Experiment 2.

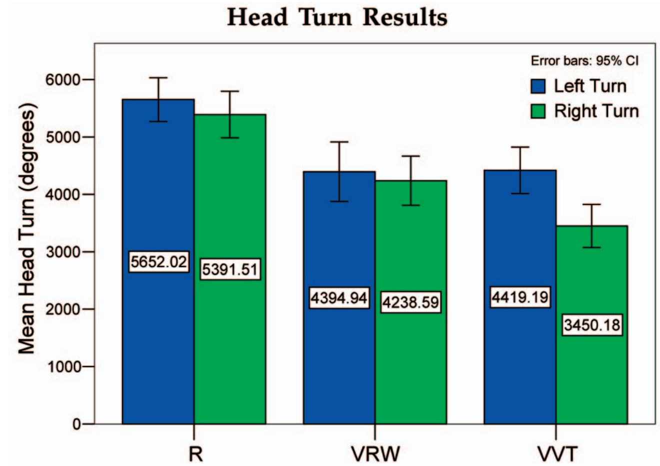

Fig. 9. Mean head turn results by direction (in total degrees turned). Participants in the VVT condition tended to favor left turns over right, while turns in the other conditions were roughly even.

VRW condition ($M = 75.67, SD = 16.52$), $p < .001$, or VVT condition ($M = 60.26, SD = 16.16$), $p < .001$. The horizontal distance covered in the VRW condition was also significantly greater than the VVT condition, $p = .004$. These results indicate that participants that explored the real environment walked the greatest distance in a set amount of time. Additionally, participants in the virtual travel condition moved the least out of all the conditions.

Similarly, the post hoc analysis revealed that participants in the R condition ($M = 10.76, SD = 3.90$) covered more vertical distance than participants in the VRW condition ($M = 8.68, SD = 3.55$), $p = .037$, or VVT condition ($M = 4.57, SD = 1.81$), $p < .001$. The vertical distance covered in the VRW condition was also significantly greater than the VVT condition, $p < .001$. These results indicate that participants that explored the real environment were the most likely to bend over to look more closely at an object that was low to the ground. Additionally, these results support the claim that the real walking technique supports this behavior more than virtual travel techniques.

4.5.8 Head Turn

A 2×3 mixed ANOVA was performed, testing the within-subjects effect of head turn direction and the between-subjects effect of experiment condition. The analysis revealed a significant interaction effect between the two independent variables, $F(2, 87) = 6.63, p = .002$. The main effect for experiment condition was also significant, $F(2, 87) = 19.48, p < .001$. There was also a significant main effect for direction of head turn, $F(1, 87) = 21.71$, $p < .001$. These results indicate that the amount of head rotation varied across the conditions, and the amount of left and right head turn was affected differently depending on the experimental condition.

Post hoc analysis investigating the between-subjects effect of experimental condition revealed that the amount of head rotation in the R condition was greater than the VRW condition and the VVT condition. The VRW condition and VVT condition were not significantly different. This indicates that participants that explored the real-world environment turned their heads more (either by looking side-to-side or by turning the body). However, travel technique in the virtual environment conditions does not appear to influence the total amount of head turn.

Fig. 9 shows a graph of left and right head turn for the different conditions. While the left and right head turn amounts for the R and VRW conditions were roughly even, participants in the VVT condition only tended to heavily favor turning toward the left. This difference between left and right head turn in this condition was highly significant, $t(29) = 6.42, p < .001$. Moreover, this trend was very noticeable during the experiment session; many participants in the VVT condition tended to "spin" in one direction only, requiring intervention to prevent tangled cables. It should be noted that only 5 out of the 90 participants were left-handed, but even those participants tended to favor left turns over the right.

4.6 Discussion

Overall, participants in the real-world condition performed significantly better on most of our measures. We conclude that there is significant room for improvement in supporting information gathering and cognition in virtual environments. However, there were many differences between the real world and virtual environment that may have contributed to these results. When wearing the HMD, field of view is considerably lesser than in the real world, and previous studies have shown that restricting field of view in a virtual environment reduces search performance and increases the amount of time spent in one area [30]. The HMD also increases weight and inertia on the head, which has been known to cause fatigue and motion sickness [31]. Additionally, visual differences between environments may have played a role, though a similar study did not find that differences in visual detail influenced navigation [10].

In spite of the differences between the real world and virtual environment, our data indicate that there are no differences between real walking and gaze-directed travel for these factors. These results are important for applications where supporting memory or cognition is an important goal. Specifically, our findings imply that for complex virtual environments which require many turns to navigate, a virtual travel technique may be substituted as a less expensive alternative to real walking. However, given numerous previous studies which have found advantages for real walking under different conditions (e.g., [8], [16], [10],

TABLE 3
Summary of Conclusions

Goal of VE Application	Preferred Travel Technique
Supporting Memory	RW or VT
Supporting Cognition	RW or VT
Similarity to Real World	RW
Faster Navigation	RW
Reducing Collisions	RW
Reducing Simulator Sickness	VT

A summary of our conclusions based on the results across experiments comparing real walking (RW) to virtual travel (VT) in complex virtual environments.

[11]), more investigation is necessary to fully understand the potential benefits of this technique over virtual travel.

The results for simulator sickness were unexpected. Previous experiments which have investigated the effects of travel technique on simulator sickness have either reported no difference [16] or lesser motion sickness when using real walking [8]. The former study took place in a simple environment requiring little physical maneuvering. The latter study required navigation through a complex maze; however, the sickness measure used was a single self-report of motion sickness, an imprecise measure which likely corresponds to nausea. Our experiment used an extensively researched and validated simulator sickness questionnaire which incorporates measures of nausea, occulomotor problems, and disorientation. We conclude, based on our results, that the navigational complexity of the environment, which required a great deal of physical maneuvering, combined with the time spent in the environment (over 6 minutes including training), resulted in increased simulator sickness for participants in the real walking condition. Participants in the virtual travel condition tended to turn about in a stationary location, and this behavior did not appear to induce simulator sickness. This suggests that virtual travel may actually be a better choice for environments requiring a great amount of physical maneuvering, especially as the amount of time immersed in the environment increases.

While real walking in the virtual world did not support as much horizontal distance covered, vertical distance covered, or total head turn as the real world condition, the virtual travel technique was even lower for all three measures. The increased difficulty of using the virtual travel controller to perform fine-grained movements may have contributed to this difference, causing participants to less likely explore seemingly insignificant areas that were inconvenient to navigate (e.g., dead ends). Additionally, virtual travel appears to introduce a tendency to favor turns in one direction over another, which we did not observe in either the real walking or real-world conditions. In summary, our data support the claim that real walking results in navigational behavior that is more similar to the real world than virtual travel.

5 Conclusion

Ultimately, the choice of travel technique depends upon the goals of the application. In Table 3, we summarize the relative strengths of these techniques that were observed across our experiments comparing real walking to virtual travel. We conclude that for complex environments requiring a large number of turns, virtual travel is an acceptable substitute for real walking if the goal of the application involves learning or reasoning based on information presented in the environment. However, for applications that require fast, efficient navigation or travel that closely resembles real-world behavior, real walking has advantages over virtual travel, which may justify the cost and space trade-offs required by this technique.

References

[1] D.A. Bowman, E. Kruijff, J.J. La Viola, and I. Poupyrev, *3D User Interfaces: Theory and Practice.* Addison Wesley Longman, 2004.
[2] J.J. Feasel, M. Whitton, and J. Wendt, "LLCM-WIP: Low-Latency, Continuous-Motion Walking-in-Place," *Proc. IEEE Symp. 3D User Interfaces,* pp. 97-104, 2008.
[3] J.N. Templeman, P.S. Denbrook, and L.E. Sibert, "Virtual Locomotion: Walking in Place through Virtual Environments," *Presence: Teleoperators and Virtual Environments,* vol. 8, no. 6, pp. 598-617, 1999.
[4] R.P. Darken, W.R. Cockayne, and D. Carmein, "The Omni-Directional Treadmill: A Locomotion Device for Virtual Worlds," *Proc. ACM Symp. User Interface Software and Technology (UIST),* pp. 213-221, 1997.
[5] G. Welch and E. Foxlin, "Motion Tracking: No Silver Bullet, but a Respectable Arsenal," *IEEE Computer Graphics and Applications,* vol. 22, no. 6, pp. 24-38, Nov./Dec. 2002.
[6] J. Templeman, L. Sibert, R. Page, and P. Denbrook, "Pointman—A Device-Based Control for Realistic Tactical Movement," *Proc. IEEE Symp. 3D User Interfaces,* 2007.
[7] M. Usoh, K. Arthur, M.C. Whitton, R. Bastos, A. Steed, M. Slater, and F.P. Brooks, "Walking > Walking-in-Place > Flying, in Virtual Environments," *Proc. ACM SIGGRAPH,* pp. 359-364, 1999.
[8] S.S. Chance, F. Gaunet, A.C. Beall, and J.M. Loomis, "Locomotion Mode Affects the Updating of Objects Encountered During Travel: The Contribution of Vestibular and Proprioceptive Inputs to Path Integration," *Presence: Teleoperators and Virtual Environments,* vol. 7, no. 2, pp. 168-178, 1998.
[9] M.C. Whitton, J.V. Cohn, J. Feasel, P. Zimmons, S. Razzaque, S.J. Poulton, B. Mc Leod, and F.P. Brooks Jr., "Comparing VE Locomotion Interfaces," *Proc. IEEE Virtual Reality Conf.,* pp. 123-130, 2005.
[10] R.A. Ruddle and S. Lessels, "For Efficient Navigational Search, Humans Require Full Physical Movement, but Not a Rich Visual Scene," *Psychological Science,* vol. 17, no. 6, pp. 460-465, 2006.
[11] R.A. Ruddle and S. Lessels, "The Benefits of Using a Walking Interface to Navigate Virtual Environments," *ACM Trans. Computer-Human Interaction,* vol. 16, no. 1, pp. 1-18, 2009.
[12] D.A. Bowman, D. Koller, and L.F. Hodges, "Travel in Immersive Virtual Environments: An Evaluation of Viewpoint Motion Control Techniques," *Proc. IEEE Virtual Reality Int'l Symp.,* pp. 45-52, 1997.
[13] D.A. Bowman, D. Koller, and L.F. Hodges, "A Methodology for the Evaluation of Travel Techniques for Immersive Virtual Environments," *Virtual Reality,* vol. 3, no. 2, pp. 120-131, 1998.
[14] M. Vidal, M.-A. Amorim, and A. Berthoz, "Navigating in a Virtual 3D Maze: How Do Egocentric and Allocentric Reference Frames Interact?" *Cognitive Brain Research,* vol. 19, no. 3, pp. 244-258, 2004.
[15] D. Jeong, C. Lee, G. Jeon, C. Song, S. Babu, and L. Hodges, "Differentiation on Information Gathering Ability in Real and Virtual World," *Proc. Int'l Conf. Pacific Graphics,* pp. 157-159, 2005.
[16] C.A. Zanbaka, B.C. Lok, S.V. Babu, A.C. Ulinski, and L.F. Hodges, "Comparison of Path Visualizations and Cognitive Measures Relative to Travel Technique in a Virtual Environment," *IEEE Trans. Visualization and Computer Graphics,* vol. 11, no. 6, pp. 694-705, Nov./Dec. 2005.
[17] D.A. Bowman, E.T. Davis, L.F. Hodges, and A.N. Badre, "Maintaining Spatial Orientation During Travel in an Immersive Virtual Environment," *Presence: Teleoperators and Virtual Environments,* vol. 8, no. 6, pp. 618-631, 1999.
[18] H.J. Spiers and E.A. Maguire, "A 'Landmark' Study on the Neural Basis of Navigation," *Nature Neuroscience,* vol. 7, no. 6, pp. 572-574, 2004.

[19] G. Wallet, H. Sauzéon, J. Rodrigues, and B. N'Kaoua, "Transfer of Spatial Knowledge from a Virtual Environment to Reality: Impact of Route Complexity and Subject's Strategy on the Exploration Mode," *J. Virtual Reality and Broadcasting,* vol. 6, no. 4, pp. 572-574, 2009.

[20] J.Z. Bakdash, S.A. Linkenauger, and D. Proffitt, "Comparing Decision-Making and Control for Learning a Virtual Environment: Backseat Drivers Learn Where They Are Going," *Proc. Human Factors and Ergonomics Soc. Ann. Meeting,* vol. 52, pp. 2117-2121, 2008.

[21] E.A. Suma, S. Babu, and L.F. Hodges, "Comparison of Travel Techniques in a Complex, Multi-Level 3D Environment," *Proc. IEEE Symp. 3D User Interfaces,* pp. 147-153, 2007.

[22] R.M. Taylor, T.C. Hudson, A. Seeger, H. Weber, J. Juliano, and A.T. Helser, "VRPN: A Device-Independent, Network-Transparent VR Peripheral System," *Proc. ACM Virtual Reality Software and Technology,* pp. 55-61, 2001.

[23] R. Kennedy, N. Lane, K. Berbaum, and M. Lilienthal, "Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness," *Int'l J. Aviation Psychology,* vol. 3, no. 3, pp. 203-220, 1993.

[24] J. Guilford and W. Zimmerman, "The Guilford-Zimmerman Aptitude Survey," *J. Applied Psychology,* vol. 32, pp. 24-34, 1948.

[25] M. Billinghurst and S. Weghorst, "The Use of Sketch Maps to Measure Cognitive Maps of Virtual Environments," *Proc. IEEE Virtual Reality Ann. Int'l Symp.,* pp. 40-47, 1995.

[26] H.Q. Dinh, N. Walker, C. Song, A. Kobayashi, and L.F. Hodges, "Evaluating the Importance of Multi-Sensory Input on Memory and the Sense of Presence in Virtual Environments," *Proc. IEEE Virtual Reality Conf.,* p. 222, 1999.

[27] B. Bloom, M. Englehart, E. Furst, W. Hill, and D. Krathwohl, *Taxonomy of Educational Objectives: Cognitive Domain.* Addison Wesley, 1956.

[28] T. Crooks, *Assessing Student Performance (Green Guide no 8).* Higher Education Research and Development Soc. Australasia (HERDSA), 1988.

[29] S.D. Young, B.D. Adelstein, and S.R. Ellis, "Demand Characteristics in Assessing Motion Sickness in a Virtual Environment: Or Does Taking a Motion Sickness Questionnaire Make You Sick?" *IEEE Trans. Visualization and Computer Graphics,* vol. 13, no. 3, pp. 422-428, May/June 2007.

[30] S. Lessels and R.A. Ruddle, "Changes in Navigational Behaviour Produced by a Wide Field of View and a High Fidelity Visual Scene," *Proc. Eurographics Symp. Virtual Environments,* pp. 71-78, 2004.

[31] P. DiZio and J. Lackner, "Altered Loading of the Head Exaccerbates Motion Sickness and Spatial Disorientation," *Proc. Aerospace Medical Assoc. Meeting,* 1992.

Evan A. Suma received the PhD degree from the University of North Carolina at Charlotte in computer science in 2010. His research interests include virtual environments, human-computer interaction, 3D user interfaces, and information visualization. He is a student member of the IEEE. For more information, see http://www.evansuma.com.

Samantha L. Finkelstein is an undergraduate student at the University of North Carolina at Charlotte in computer science and psychology. Her research interests include virtual environments, virtual humans, cognition, perception, and humancomputer interaction. For more information, see http://fcl.uncc.edu/slfink/.

Myra Reid received the BS degree in psychology from the University of North Carolina at Charlotte in 2009. She is currently working toward the doctorate degree in cognitive science at Mississippi State University. Her current research interests include memory and metamemory.

Sabarish V. Babu received the PhD degree from the Department of Computer Science at the University of North Carolina at Charlotte in 2007. He is an assistant professor in the School of Computing at Clemson University. His research interests include virtual humans, embodied conversational agents, applied perception and cognition in virtual environments, 3D interaction, and visualization. He is a member of the IEEE. For more information, see http://people.clemson.edu/~sbabu/.

Amy C. Ulinski received the PhD degree in computer science from the University of North Carolina at Charlotte in 2008. Currently, she is a postdoctoral fellow in the School of Computing at Clemson University. Her research interests include human-computer interaction, 3D user interfaces, visualization, virtual environments, and virtual humans. She is a member of the IEEE and the IEEE Computer Society. For more information, see http://www.amyulinski.com.

Larry F. Hodges is the hf Flagship Endowed Chair Director of the School of Computing at Clemson University. His research interests include virtual environments, 3D user interfaces, and human-virtual human interaction. In 2006, he received the IEEE Virtual Reality Career Award for his contributions to clinical applications of virtual reality. He is a member of the IEEE. For more information, see http://www.clemson.edu/~lfh/.