Comparison of Travel Techniques in a Complex, Multi-Level 3D Environment

Evan A. Suma*　　Sabarish Babu　　Larry F. Hodges

University of North Carolina at Charlotte

Abstract

This paper reports on a study that compares three different methods of travel in a complex, multi-level virtual environment using a between-subjects design. A real walking travel technique was compared to two common virtual travel techniques. Participants explored a two-story 3D maze at their own pace and completed four post-tests requiring them to remember different aspects of the environment. Testing tasks included recall of objects from the environment, recognition of objects present and not present, sketching of maps, and placing objects on a map. We also analyzed task completion time and collision data captured during the experiment session. Participants that utilized the real walking technique were able to place more objects correctly on a map, completed the maze faster, and experienced fewer collisions with the environment. While none of the conditions outperformed each other on any other tests, our results indicate that for tasks involving the naive exploration of a complex, multi-level 3D environment, the real walking technique supports a more efficient exploration than common virtual travel techniques. While there was a consistent trend of better performance on our measures for the real walking technique, it is not clear from our data that the benefits of real walking in these types of environments always justify the cost and space trade-offs of maintaining a wide-area tracking system.

CR Categories and Subject Descriptors: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems – Artificial, augmented, and virtual realities; I.3.6 [Computer Graphics]: Methodology and Techniques – Interaction techniques; I.3.7 [Computer Graphics]: - Three-Dimensional Graphics and Realism – Virtual reality.

Additional Keywords: evaluation, navigation, user study, virtual reality

1 Introduction

1.1 Motivation

Navigation in a virtual environment is commonly divided into two components: motor and cognitive [1]. The motor component, known as travel, refers to the movement of the viewpoint from one location to another. The cognitive component, known as wayfinding, is the process of defining a path through an environment. In this study, we investigate the travel component of navigation, and we explore the effects of travel technique on users' ability to learn about a complex, multi-level virtual environment.

*email:{easuma, sbabu, lfhodges}@uncc.edu

IEEE Symposium on 3D User Interfaces 2007
March 10 - 11, Charlotte, North Carolina, USA
1-4244-0906-3/07/$20.00 ©2007 IEEE

Immersive virtual environments (IVEs) attempt to give the user a sense of being present within a virtual space. Several IVEs, such as architecture walkthroughs and games, use a first person perspective [2]. In these systems, control of view-point is typically accomplished by either head motion and/or using a virtual travel technique (such as using a joystick) in order to simulate walking through the IVE. Some virtual environment systems use tracking equipment, typically attached to a user's head, to allow the user to control the viewpoint and improve level of immersion [3]. Welch and Foxlin provide a comprehensive overview of current tracking systems [4]. Indoor systems for head tracking in IVEs can be categorized into three major subsets:

- **3DoF Orientation Only Tracking Systems:** Tracker reports only the orientation of the device (e.g. Intersense InertiaCube).
- **6DoF Limited-Area Tracking Systems:** Tracker reports position and orientation, restricted to a workspace some distance from an emitter [5] (e.g. Polhemus Fastrack, Ascension Flock of Birds).
- **6DoF Wide-Area Tracking Systems:** Tracker reports position and orientation in a large area, typically the size of a room (e.g. Hiball, Intersense IS-900).

If the virtual space is larger than the physical tracking space, navigation is typically controlled through the use of a tracked joystick or mouse. Locomotion is most commonly simulated via one of two methods, either moving the user in the direction he is looking or in the direction he is pointing, and is enabled when the user presses a button [6]. If the virtual space is smaller than the physical tracking space, travel may be accomplished by using a wide-area tracking system to allow a user to physically walk about the space.

The benefits of using wide-area tracking equipment in which users can explore a virtual environment in a natural manner come from recent advances in wide area position and orientation tracking technology that now enable us to track a users movement through spaces that are larger than the 1.5-3 meter diameter spaces normally tracked by electromagnetic tracking devices [4]. However, wide-area position and orientation tracking systems such as the Intersense IS-900 or the 3rdTech Hiball are expensive, and the cost of such a system increases with increase in tracker workspace area. Additionally, these systems require a large amount of empty space to provide an area for the user to freely walk around. Nevertheless, this technology enables us to measure the relative efficacy of real walking in an immersive virtual environment as opposed to simulated walking metaphors.

In this paper, we describe a user study in which we investigate the differences between real walking and the two most common virtual travel techniques in a complex, multi-level immersive virtual environment. **Our hypothesis predicted that participants that used the real walking technique would exhibit superior performance on post-tests about the layout and contents of the environment.**

1.2 Previous Work

1.2.1 Task Performance in Immersive Virtual Environments

Previous studies suggest certain tasks and applications benefit from IVEs. Bowman, Koller, and Hodges 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 [6]. They also report that motion techniques that 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, reported sense of presence has been rated higher in real walking and walking in place compared to joystick "flying" conditions [7].

Pausch et al. showed that search tasks could be done more effectively in a tracked head mounted display (HMD) versus an untracked HMD [8]. Ruddel et al. showed that navigating large-scale virtual environments was significantly faster in a tracked HMD versus a desktop display [9].

1.2.2 Cognition in Immersive Virtual Environments

Mania et al. compared recall of different shaped objects in an IVE displayed on an HMD in mono or stereo, with or without head tracking, and on a desktop monitor with the real world task situation [10]. Participants' memory awareness states across conditions varied greatly; in particular, they found that experimental conditions that incorporated head tracking were not associated with visually-induced recollections.

Vidal et. al. compared ability to memorize a complex 3D maze when using different reference frames for navigation [11]. They 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.

Some studies have compared virtual and real walking through a complex virtual environment such as a maze. Chance et al. compared actual walking through a virtual maze environment to virtual travel and 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 [12]. They also found that participants scored higher in mental map tests and basic navigation tests in the real walking condition. Participants in the real walking condition also showed low degree of motion sickness as compared to participants in the virtual travel condition.

Jeong et. al. compared the information gathering ability of participants in a real environment vs. exploring a virtual environment using virtual travel [13]. They found that participants who explored the real world gathered more information than participants who explored the virtual world. They attribute the difference to the cognitive load associated with exploration of the virtual world using a virtual travel technique.

Zanbaka et. al. compared the differences on cognition and understanding of a small virtual room when explored using common joystick-based travel techniques versus walking about the space in a natural manner [14]. They found that participants who explored the virtual environment in a natural manner scored significantly higher in the understanding and application as well as higher mental processes portion of the cognition questionnaire as compared to virtual travel techniques.

2 System Overview

2.1 Equipment

For this study, we used the VR1280 head-mounted display (HMD) developed by Virtual Research Systems. This HMD provides a stereoscopic view with a resolution of 1280 x 1024 for each eye. Tracking was accomplished using a 3rdTech HiBall 3100 wide-area tracking system. This system provides optical tracking with six degrees of freedom for up to 2 separate trackers. One tracker was mounted on top of the HMD, with the other tracker mounted on a handheld device used to control movement in the virtual travel conditions.

The environment was run on a Dell Pentium 4 3.0Ghz PC with 1GB of RAM and an nVidia Geforce 6800 graphics card, which provided 2 separate VGA output channels to the head-mounted display at 60hz.

2.2 Virtual Environment

2.2.1 Software

The virtual environment was developed using the 3D GameStudio game development system, which provided authoring tools, 3D rendering, scripting, and collision detection. Add-on modules were written in C++ and integrated into the game engine to facilitate communication with the tracking system.

2.2.2 Experiment Environment

For this experiment, we designed a virtual environment that was larger and more complex in terms of navigation and structure than was done in our previous studies (Fig. 1). The dimensions of the environment were precisely designed to fit our 16' x 14' tracking area, leaving 6-inch borders around the perimeter of the area to avoid collisions with the physical environment. The experiment environment was designed as a three-dimensional 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, 3).

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. Collision detection was utilized to prevent the participant from walking through walls. Additionally, in the event of a collision with a virtual wall, the simulation engine generated a buzzing sound as an audio cue to notify the participant.

A total of 18 objects were placed throughout the environment. The collection included 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.

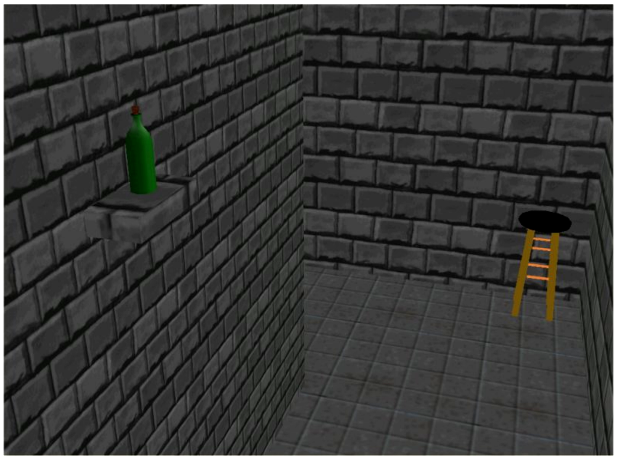

Figure 1. Screenshot of Experiment Environment

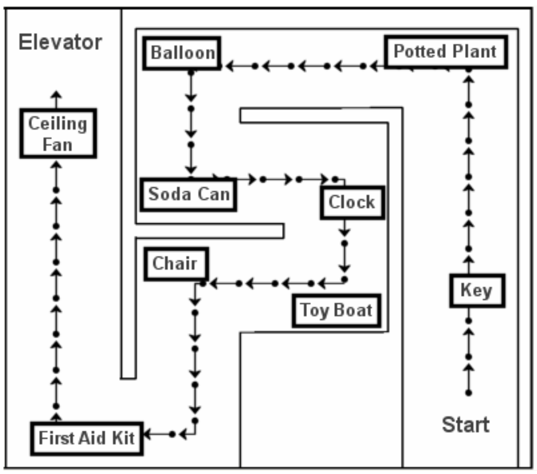

Figure 2. Map of Level 1

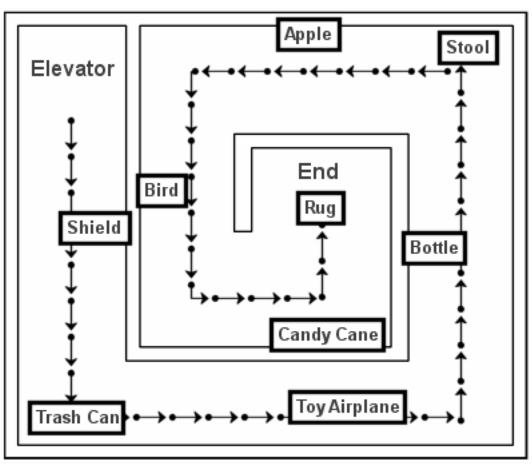

Figure 3. Map of Level 2

3 Study Design

3.1 Design

To further explore the differences between real walking and common virtual travel methods, we conducted a user study with travel technique as the independent variable. The experiment 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 (Fig. 4).

2. **Moving Where Looking (MWL):** Participants used a handheld device to move forward in the direction their head was pointing (Fig. 5).

3. **Moving Where Pointing (MWP):** Participants used a handheld device to move forward in the direction their hand was pointing (Fig. 5)

Figure 4. Participant in RW Condition

Figure 5. Participant in MWL/MWP Conditions

In the MWL and MWP conditions, the physical space was restricted by a 4' x 4' enclosure constructed from PVC pipe. This restriction simulated the physical limitations of limited-area trackers that typically accurately track an area only 1-2 meters in diameter. Travel was facilitated using a device that was held in the dominant hand (Fig. 6). When the participant pressed the trigger button, the view in the virtual environment was translated forward in the appropriate direction. To control the speed of movement, the participant used a secondary device held in the non-dominant hand. The participant manipulated a thumb joystick on this device which acted as a throttle. A vertical speed bar was presented on the right side of the HMD screen as visual notification of the currently selected movement speed.

Our hypothesis predicted that participants that used 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.

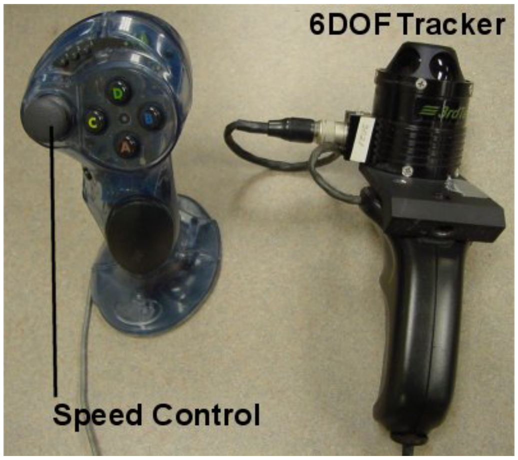

Figure 6. Handheld Devices for MWL/MWP

3.2 Measures

3.2.1 Simulator Sickness

Simulator sickness was measured using the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [15]. The questionnaire was administered immediately before and after the virtual reality session.

3.2.2 Spatial Ability

Spatial ability was measured using the Guilford-Zimmerman Aptitude Survey Part 5: Spatial Orientation [16]. The test consisted of 60 questions relating to spatial position and orientation with a maximum time limit of 10 minutes.

3.2.3 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.

3.2.4 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 correct answers was summed to provide a score from 0 to 18, with higher numbers corresponding to better performance. Participants were allowed up to 8 minutes to complete this test.

3.2.5 Sketch Maps

Participants were given two blank sheets of paper and instructed to sketch 2 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 3 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 [14] and [17]. Graders were instructed to evaluate the maps based upon a 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.

3.2.6 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. 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.

3.2.7 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.

3.3 Participant Information

A total of 49 participants completed the study with 17 participants in the RW condition, 17 in the MWL condition, and 15 in the MWP condition. Participants were recruited from announcements in summer-school courses, fliers, and word-of-mouth, and were required to be able to communicate in written English.

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 first read the Participant Information Sheet and was asked if he had any questions. Next, he read and electronically signed the Informed Consent form. He then took the spatial orientation test. Finally, he completed the pre-test for simulator sickness.

3.4.2 Experiment

The participant was led to the experiment area of the lab where he was introduced to the equipment. The experimenter explained the experiment procedure and asked the participant if he had any questions. Next, the participant was fitted with the head-mounted display and handheld controllers (for the MWL and MWP conditions).

Before entering the experiment environment, the participant was exposed to a brief training environment. During this training session, the controls and equipment were explained to him, and he was given a simple task to complete. The participant was instructed to look at an object on the opposite side of the room and move to it. Once completed, the participant repeated this process for another object across the room. The participant was then asked if he was ready to begin the experiment and if he had any questions.

When the participant was ready, the experiment environment was loaded and the participant was instructed to explore the maze until he reached the end, paying attention to the environment as he went through. The participant was instructed to complete the maze at his own pace and was given no time limit. The experiment session ended when he reached the end of the maze.

3.4.3 Post-Experiment

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

1. Object Recall
2. Object Recognition
3. Sketch Maps
4. Object Placement

After completing all tests, the subject was debriefed and asked if he had any questions.

4 RESULTS AND DISCUSSION

4.1 Pre-Tests

4.1.1 Simulator Sickness

A 2x3 mixed ANOVA was performed, testing the within-subjects effect of SSQ score before and after instruction and the between-subjects effect of travel technique. This experimental design provided an estimated power of .65 to detect medium-size between-subjects effects and an estimated power of .76 to detect medium-size within-subjects effects. The analysis revealed a non-significant interaction, $F(2,46) = .10$, $p = .902$. The main effect for SSQ score was not significant, $F(1,46) = .58$, $p = .449$, nor was the main effect for travel technique, $F(2,46) = .49$, $p = .615$. These results indicate reported simulator sickness did not significantly change from before ($M = 13.43$, $SD = 13.04$) to after instruction ($M = 15.57$, $SD = 17.86$). Additionally, the degree of simulator sickness did not vary across the different travel techniques.

4.1.2 Spatial Ability

Preliminary analysis of the scores indicated that 8 out of 15 participants in the MWP condition received nonpositive scores on the test, compared to 1 in the MWL condition and 0 in the RW condition. The method by which the scores were graded implies that a participant that received a nonpositive score answered four times as many incorrect answers as correct answers. Given that each question has one correct and four incorrect possible answers, a nonpositive score indicates that the participant was guessing and did not seriously attempt to complete the test. We eliminated participants with nonpositive scores from this analysis. Given the large number and uneven distribution of eliminated scores, it is difficult to draw conclusions from this data.

These scores were treated with a one-way between-subjects ANOVA across all conditions with a significance level of $\alpha = .05$. The results were significant, $F(2,37) = 3.73$, $p = .033$. Post hoc analysis with the Tukey HSD test revealed that participants in the RW condition ($M = 12.18$, $SD = 5.44$) received significantly higher scores than those in the MWL condition ($M = 6.89$, $SD = 5.11$), $p = .026$. Participants in the RW condition scored higher than the MWP condition ($M = 9.32$, $SD = 6.82$), but the difference was not significant, $p = .494$. Additionally, the MWL and MWP conditions were not significantly different, $p = .603$.

Considering that the participants were assigned to different groups at random, a significant difference on a pre-test is possible, but highly unlikely. Given uniform instructions and testing experience, we cannot explain these results other than by a statistical fluke.

To explore the implications of this distribution, the relationships between the spatial ability scores and the other measures were assessed using Pearson correlation coefficients (see Table 1). There was a significant positive relationship between spatial ability and object placement, $r(40) = .36$, $p = .023$. All other relationships were not significant. This indicates that we should interpret the results of the object placement test with some caution.

Table 1. Spatial Ability Correlations

	r-value	p-value
Recall	.27	.098
Recognition	.31	.059
Sketch Maps	.13	.439
Object Placement*	.36	.023
Time	.00	.981
Collisions	-.19	.238

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

4.2 Post-Tests

Results from the object recall, object recognition, sketch map, and object placement tests were each treated with a one-way between-subjects ANOVA across all conditions with a significance level of $\alpha = .05$. This experimental design provided an estimated power of .67 to detect large-size effects. The mean results of these tests are shown in Table 2.

4.2.1 Object Recall

The ANOVA was not significant, $F(2,46) = .81$, $p = .450$. This suggests that none of the travel techniques positively or negatively affect the ability to recall objects from a 3D environment.

4.2.2 Object Recognition

The ANOVA was not significant, $F(2,44) = .42$, $p = .663$. This suggests that none of the travel techniques positively or negatively affect the ability to recognize an object from a 3D environment.

4.2.3 Sketch Maps

The ANOVA was not significant, $F(2,46) = 2.19$, $p = .123$. This suggests that none of the travel techniques positively or negatively affect the ability to reproduce a map of a 3D environment.

4.2.4 Object Placement

The ANOVA was significant, $F(2,46) = 3.90$, $p = .027$. Post hoc analysis using the Tukey HSD test indicated that the difference between the RW and MWP condition was significant, $p = .021$. The difference between the RW and MWL condition was not significant, $p = .456$, nor was the difference between the MWL and MWP condition, $p = .247$. While this may indicate that the real walking technique facilitated the ability to remember object locations in a 3D environment better than the moving where pointing technique, it is important to note that the object placement measure correlated with the spatial ability test. It is possible that these results were biased by the unequal distribution of spatial orientation across groups.

Table 2. Mean Post-Test Results

	RW	MWL	MWP
Object Recall	7.53	7.24	6.60
Object Recognition	8.81	8.53	7.79
Sketch Maps	2.86	2.71	2.30
Object Placement*	3.29	2.53	1.47

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

4.3 Experiment Data

The time to complete the maze and the number of collisions with the environment were each treated with a one-way between-subjects ANOVA across all conditions with a significance level of $\alpha = .05$. This experimental design provided an estimated power of .67 to detect large-size effects. The mean results of this data are shown in Table 3.

4.3.1 Time

The ANOVA was significant, $F(2, 45) = 8.22$, $p = .001$. Post hoc analysis with the Tukey HSD test revealed significant differences between the MWP condition and the RW ($p = .001$) and MWL conditions, $p = .042$. The RW and MWL conditions were not significantly different, $p = .248$. These results indicate that the real walking and moving where looking techniques allow a participant to complete a task involving travel in a 3D environment more efficiently than the moving where pointing technique.

4.3.2 Collisions

The ANOVA was significant, $F(2, 45) = 5.58$, $p = .007$. Post hoc analysis using the Tukey HSD test revealed a significant difference between the RW and MWP conditions, $p = .005$. The MWL condition was not significantly different from the RW condition, $p = .322$, or the MWP condition, $p = .135$. These results indicate that the real walking technique allows a participant to explore a 3D environment with fewer collisions with the boundaries of the environment than the moving where pointing technique.

Table 3. Mean Experiment Data Results

	RW	MWL	MWP
Time (sec.)*	104.67	137.55	191.01
Collisions*	.24	1.65	3.64

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

5 Discussion

Participants using the real walking technique did no worse than those using the virtual travel techniques on any of the post-tests, but completed the environment in much 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 real walking technique provides a more efficient method of travel. Additionally, using the real walking technique reduced the number of collisions with virtual walls of the environment, indicating that this technique could be beneficial for applications where it is important to maintain a high degree of immersion.

Our results are not as strong as some of the previous studies that have examined the differences among travel techniques. One possible explanation for this discrepancy is that the learning benefits of the real walking technique diminish as the environment becomes sufficiently large and complex. While the real walking technique did not outperform virtual travel techniques as we had initially hypothesized, it is interesting to note that that mean performance followed a consistent trend throughout the entire experiment, with RW participants performing best, MWL participants in the middle, and MWP participants performing worst. The fact that this held true for every test could indicate that there was a difference that this experimental design lacked the statistical power to detect.

While it is possible that the skewed distribution of spatial orientation biased our results, the unusual results from the spatial orientation test means these scores should be interpreted with skepticism. Further investigation is needed to draw conclusive results.

It is also important to note that the participants were drawn from a pool largely composed of university students. The degree to which these results can be generalized to the overall population is not known.

6 Summary and Future Work

In this study, we compared the real walking travel technique with two common virtual travel techniques in a complex 3D environment. To this end, we designed a two-story virtual maze with objects placed throughout the environment. Participants were assigned to one of three travel conditions and instructed to complete their maze at their own pace. We compared performance on four tests requiring a participant to remember different aspects of the environment, and time and collision data from the experiment was captured and analyzed.

Our results revealed that the real walking technique facilitated quicker exploration with fewer collisions with walls of the environment. Participants in the RW condition performed at least as well on the post-tests, although they did not outperform the participants in the MWL and MWP conditions on most of the measures as we had initially hypothesized. Participants in the RW condition were able to better remember the locations of the objects in the environment, but these results are mitigated by a possible uneven distribution of spatial ability among groups. Finally, there was a consistent trend where participants in the RW condition performed better, but further study with a stronger experimental design is necessary to understand the implications of this trend.

These results indicate that for tasks involving the naive exploration of a large, complex 3D environment, the real walking technique supports a more efficient exploration than common virtual travel techniques. While there was a consistent trend of better performance on our measures for the real walking technique, it is not clear from our data that the benefits of real walking in these types of environments always justify the cost and space trade-offs of maintaining a wide-area tracking system.

Reference

[1] D. Bowman, E. Kruijff, J. LaViola, and I. Poupyrev, "An Introduction to 3D User Interface Design," Presence: Teleoperators and Virtual Environments, vol. 10, no. 1, pp. 96-108, 2001.

[2] F.P. Brooks, Jr., "Walk through – a dynamic graphics system for simulating virtual buildings," Proceedings of 1986 Workshop on Interactive 3D Graphics, pp. 9-21, 1986.

[3] M. Slater and S. Wilbur, "A Framework for Immersive Virtual Environments [FIVE]: Speculations on the Role of Presence in Virtual Environments," Presence: Teleoperators and Virtual Environments, vol. 6, no. 6, pp. 603-616, MIT Press, 1997.

[4] G. Welch and E. Foxlin, "Motion Tracking: No Silver Bullet, but a Respectable Arsenal," IEEE Computer Graphics and Applications,

special issue on "Tracking," vol. 22, no. 6, pp. 24-38, Nov./Dec. 2002.

[5] K. Meyer, H. Applewhite, and F. Biocca, "A survey of position trackers," Presence: Teleoperators and Virtual Environments, vol. 1, no. 2, pp. 173-200, 1992.

[6] D. Bowman, D. Koller, and L. F. Hodges, "Travel in immersive virtual environments: an evaluation of viewpoint motion control techniques," Proceedings of the Virtual Reality Annual International Symposium, pp. 45-52, 1997.

[7] M. Usoh , K. Arthur , M. C. Whitton , R. Bastos , A. Steed, M. Slater, and F. P. Brooks, Jr., "Walking > walking-in-place > flying, in virtual environments", Proceedings of the 26th annual conference on Computer graphics and interactive techniques, pp. 359-364, 1999.

[8] R. Pausch, D. Proffitt, and G. Williams, "Quantifying immersion in virtual reality," Proceedings of the 24th annual conference on Computer graphics and interactive techniques, pp. 13-18, August 1997.

[9] R. A. Ruddle, S. J. Payne, and D. M. Jones, "Navigating largescale virtual environments: What differences occur between helmet-mounted and desk-top displays?" Presence: Teleoperators and Virtual Environments, vol. 8, no. 2, pp. 157-168. 1999.

[10] K. Mania, T. Troscianko, R. Hawkes, and A. Chalmers, "Fidelity Metrics for Virtual Environment Simulations based on Spatial Memory Awareness States," Presence, Teleoperators and Virtual Environments, vol. 12, no. 3, pp. 296-310, 2003.

[11] 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 19(3), pp. 244-258, 2004.

[12] S. Chance, F. Gaunet, A. Beall, and J. Loomis, "Locomotion Mode Affects the Updating of Objects Encountered During Travel," Presence: Teleoperators and Virtual Environments, vol. 7, no. 2, pp.168-178, 1998.

[13] D.H. Jeong, C.S. Lee, G.B. Jeon, C.G. Song, S. Babu, and L.F. Hodges, "Differentiation on Information Gathering Ability in Real and Virtual World", in the Proceedings of the International Conference on Pacific Graphics 2005, Short paper, pp.157 – 159.

[14] C. Zanbaka, B. Lok, S. Babu, A. Ulinski, and L.F. Hodges, "Comparison of path visualizations and cognitive measures relative to travel technique in a virtual environment," IEEE Transactions on Visualization and Computer Graphics 11, pp. 694-705, 2005.

[15] R.S. Kennedy, N.E. Lane, K.S. Berbaum, and M.G. Lilienthal, "Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness," The International Journal of Aviation Psychology, 3(3), pp. 203-220, 1993.

[16] J.P. Guilford, W.S. Zimmerman, "The Guilford-Zimmerman Aptitude Survey," Journal of Applied Psychology, 32, pp. 24-34, 1948.

[17] M. Billinghurst and S. Weghorst, "The Use of Sketch Maps to Measure Cognitive Maps of Virtual Environments," Proceedings of IEEE 1995 Virtual Reality International Symposium, pp. 40-47, 1995.