EXPERIMENTAL EVALUATION OF THE COGNITIVE EFFECTS OF TRAVEL TECHNIQUE IN IMMERSIVE VIRTUAL ENVIRONMENTS

by

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ABSTRACT

EVAN A. SUMA. Experimental evaluation of the cognitive effects of travel technique in immersive virtual environments. (Under the direction of DR. LARRY F. HODGES)

Navigation is one of the most common and universal interaction tasks performed with 3D user interfaces, and different travel techniques can have a strong influence on a user's exploration and overall experience of a virtual environment. Real walking is considered to be the most natural technique since it mirrors the way most people move about in the real world. However, due to practical limitations, virtual travel techniques are more commonly used in virtual reality applications. Although recent advantages in tracking technology have made real walking viable for many applications, the benefits and drawbacks of this technique are not well understood, particularly in relation to human cognition.

To investigate the cognitive effects of real walking, a series of three user studies were conducted to experimentally evaluate common travel techniques for immersive virtual environments using head-mounted displays. In general, these studies have identified criteria where real walking provides notable benefits, and conversely they have demonstrated that virtual travel techniques can be used as less expensive substitutes under the right conditions. Based on the results of these studies, guidelines were developed to outline the advantages and disadvantages of these techniques with respect to the particular goals of the virtual environment. Developers of future virtual reality applications may use these guidelines to weigh the benefits of using a certain travel technique against potential drawbacks or practical limitations.

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CHAPTER 1: INTRODUCTION

Navigation is one of the most common and universal tasks performed when interacting with 3D user interfaces [12]. While moving around in the real world usually occurs without conscious effort, controlling the viewpoint is often disorienting and difficult for novice users in immersive virtual environments, especially in head-mounted displays when the user's physical body is not immediately visible. Of all the techniques that have been developed to support intuitive travel in virtual environments, walking is the most natural since it mirrors the way most people move about in the real world. However, the practical drawbacks of this approach make empirical evaluation against cheaper alternatives valuable to justify the potential tradeoffs necessary to support real walking. Additionally, given the critical role of navigation for virtual environments and 3D user interfaces in general, it is vitally important to study the relative efficacy of different techniques to provide a theoretical groundwork for the design of these novel interfaces. A wide array of techniques have been developed for traveling in immersive virtual environments, each with its own set of advantages and disadvantages, and the choice of which method to use often depends upon the goals of the specific application. The purpose of this work is to experimentally evaluate these techniques to guide future design decisions for virtual reality applications.

1.1   Immersive Virtual Environments

Immersive virtual environments attempt to give the user a sense of being present within a virtual space, usually through the use of a first-person perspective [13]. In this work, we focus on immersive virtual environments which use head-mounted displays (HMDs), as opposed to stereoscopic monitors or surround-screen projection-based systems such as the CAVE [19]. In these systems, control of the viewpoint is typically accomplished, either wholly or in part, by using motion tracking equipment which is typically attached to the user's head [60]. The measurements from the tracking system are used to calculate the correct stereoscopic view and are also commonly used to support navigation and interaction with the environment. Welch and Foxlin provide a comprehensive overview of current tracking systems [77]. Indoor systems for head tracking in immersive virtual environments can be categorized into three major subsets:

- **3DoF Orientation Only Tracking Systems:** Tracker reports only the orientation of the device. These trackers are relatively inexpensive compared to the other types. (e.g. Intersense InertiaCube)

- **6DoF Limited-Area Tracking Systems:** Tracker reports position and orientation, restricted to a workspace some distance from an emitter [45]. These trackers are typically limited to approximately 5-10 foot diameter spaces with degrading performance as distance from the emitter increases. (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. These are relatively more expensive tracking systems, and the cost increases with a larger workspace area. (e.g. 3rdTech Hiball, Intersense IS-900)

The type of motion tracking used in a virtual reality application determines which navigation and interaction techniques may be utilized. Thus, the process of choosing appropriate techniques is not a purely theoretical decision, but involves the practical concern of weighing the benefits of a particular technique against the costs of the required tracking technology.

1.2   Navigation in Virtual Environments

The overall process of navigating in a virtual environment is commonly divided into two components [12]. The motor component of navigation, known as *travel*, refers to the physical control of the user's viewpoint in a three-dimensional environment. This is contrasted with *wayfinding*, which involves the cognitive processes of defining a path through the environment. Various methods of supporting travel have been introduced. These techniques can either be active (where the user directly controls movement), passive (where the system controls movement), or a combination of the two [12]. Our work focuses on active techniques, which we divide into three general categories:

- *Real walking* techniques allow the user to walk about the space in a natural manner.

- *Walking-in-place* techniques attempt to replicate the physical energy and mo-

tions of walking while keeping the user in a limited physical area.

- *Virtual travel* refers to a broad class of techniques that do not imitate physical movements, instead using some other method, such as a joystick, to control locomotion.

When using real walking, the viewpoint in the virtual environment corresponds directly to the user's position and orientation in the real world. Usually, this implies a direct mapping from the measurements of the tracking system into the coordinate space of the virtual environment. This method provides a natural method of moving through a virtual environment, allowing the same intuitive motions that people use to locomote in the real world. While conceptually simple, this technique is often difficult to implement because size of the desired virtual environment often exceeds the physical tracked space available for walking, making this technique impractical for settings with limited physical workspace. In addition, to support a large enough walking space for practical use, a wide-area tracking system needs to be used, which increases the hardware cost of the application.

The simplest method of implementing a walking-in-place technique requires the user to march in a stationary location (e.g. [35][59][71][80]). When using these techniques, the motions of the feet are tracked and used to propel the user's viewpoint forward. While these methods attempt to replicate the energy and motions of real walking, the motions of marching-in-place are not an exact match to the real world. Mechanical devices such as treadmills (e.g. [21][34][58]) and bicycles (e.g. [5]) have also been developed to simulate real motion when traveling.

Virtual travel techniques are the most commonly used methods of travel because they allow for arbitrarily large virtual environments regardless of physical workspace. They are also required by all desktop-based VR applications. Multiple taxonomies have been developed to classify these techniques based on a wide range of criteria. Bowman et al. described a taxonomy of virtual travel techniques based on a decomposition of travel subtasks [10]. Alternatively, classification schemes for these techniques based on the level of user control [9] or interaction metaphor [12] have also been proposed. Perhaps the most comprehensive taxonomy was described by Arns, which improved on previous taxonomies by adding the distinction between physical movement and virtual movement in terms of rotation and translation [2][3].

We are concerned with steering techniques, which allow continuous control of the direction of travel relative to user's current viewpoint. These are the most common techniques used in immersive virtual environments since they are the most similar to real world travel. Alternatively, proposed methods of travel which are not steering-based include, but are not limited to, route-planning [9], world-in-miniature techniques [64], ray-casting selection [83], or widget-based travel [30][38]. In contrast to steering, these methods are considered "magic" techniques because they employ metaphors which are not replicable in the real world.

Steering techniques are most commonly implemented in immersive virtual environments by using trackers to determine direction of movement and a handheld device to control velocity. While not limited to any specific interaction device, commodity interface hardware such as joysticks or mice are typically used. However, specialized six degree-of-freedom input devices have also been developed for interaction in three

dimensions [28] [40].

The following steering techniques are most commonly used in immersive virtual environments:

- *Gaze-directed* steering translates the viewpoint forward in the direction the user is looking. This is the most common steering method and is often considered the "default" technique. It also does not require any additional tracking if the application already uses head tracking to calculate the view.

- *Pointing* techniques translate the viewpoint in the direction indicated by the user's hand. While this requires the addition of a hand tracker, this technique avoids the coupling of gaze and travel direction, allowing the user to move in one direction while looking in another. The tracker can often be mounted directly to the handheld device used to control movement. Pointing is generally considered to be less intuitive, resulting in increased difficulty for novice users.

- *Torso-directed* steering translates the viewpoint in the direction indicated by the user's torso. Like pointing, this technique decouples the gaze and movement direction; however, this method more naturally corresponds to movement in the real world. Thus, it should be easier and more intuitive than pointing, though this has not been experimentally verified [12]. However, this technique is limited to motion in the horizontal plane, and also requires an additional tracker to be mounted on the user's body.

1.3   Evaluation of Travel Techniques

When proposing a new system, designers need to take into account the cost and space requirements of the required tracking technology. For some applications, the benefits of using a natural, intuitive method such as real walking may justify the increased cost and space requirements of a wide-area tracking system. However, there may exist virtual travel techniques which will accomplish the desired goal just as well with a less expensive tracker that requires less physical workspace. Given the wide array of alternative virtual travel methods, experimental evaluation of these techniques can have significant implications for the design of virtual reality applications.

It is widely accepted that real walking is the most natural and intuitive method of controlling the viewpoint in a virtual environment. Thus, we expect users to be able to use this technique with minimal cognitive difficulty. Since virtual travel techniques require varying degrees of direct control by the user which may not be obvious from experiences in the real world, we would expect them to impose a greater cognitive demand than walking. Studying the cognitive difficulty of travel is important since this can have a strong impact on the user's experiences and task performance in a virtual environment. For example, in a recent study, Elmqvist et al. showed a relationship between the cognitive effort of navigation and the ability of users to build a cognitive map of the environment [24]. Given that navigation is a fundamental task in an immersive virtual environment, a difficult travel technique could potentially interfere with important cognitive activities such as information gathering, learning and reasoning, or attention. Evaluation with respect to these phenomena are significant for

a variety of domains, including, but not limited to, training, education, architecture, industrial design, and visualization.

In addition to cognition, different travel techniques may also impact a user's sense of presence in a virtual environment, which is the feeling of actually being present in the virtual world [73]. Since different techniques require varying amounts of physical movement, they may differ in the amount of simulator sickness caused by the system, which is a well-recognized side effect of exposure to immersive virtual environments. Additionally, some methods may be superior in terms of performance-based metrics such as speed or accuracy of the navigation task. Also, certain techniques may simply be preferred by users on subjective ratings, regardless of the results of quantitative measures. Ultimately, it is unlikely that there exists a single "silver-bullet" technique which will outperform all others on every measure. As such, it is up to the designers of virtual reality applications to decide which criteria are important, using the results of experimental evaluation to guide their decisions.

1.4 Dissertation Overview

The purpose of the research presented in this dissertation is to experimentally evaluate the advantages and disadvantages of real walking compared to common steering techniques for immersive virtual environments that use head-mounted displays. Three experiments were conducted:

- **Experiment 1** evaluated real walking, gaze-directed, and pointing-directed travel on measures of information gathering and navigation task performance in a multi-level virtual maze. This experiment used a more complex environment

than previous studies comparing the cognitive effects of these techniques.

- **Experiment 2** compared real walking and gaze-directed travel in a virtual maze to walking in an identical real-world environment. This experiment allowed us to further investigate open questions raised in the previous experiment and also evaluate the similarity of these travel techniques to real world behavior.

- **Experiment 3** evaluated the effects of real walking, gaze-directed, pointing-directed, and torso-directed travel on a divided attention task in a virtual environment. This task provided a more sensitive measurement of cognitive difficulty and resolved several confounding factors from previous studies.

In general, these studies have identified criteria where real walking provides notable benefits, and conversely they have demonstrated that virtual travel techniques can be used as less expensive substitutes under the right conditions. Based on the results of these experiments, we developed guidelines which outline the advantages and disadvantages of the four techniques with respect to the particular goals of the virtual environment application.

This proposal is organized as follows. Chapter 2 outlines the previous work which is relevant to the evaluation of virtual environment travel techniques. Chapters 3, 4, and 5 describe each of the three experiments that were conducted. In Chapter 6, the implications of our results and guidelines for virtual environment developers are presented and discussed. The dissertation is then concluded in Chapter 7.

CHAPTER 2: RELATED WORK

Navigation in immersive virtual environments has been investigated by many researchers. Distinct from travel techniques, wayfinding issues have been the subject of numerous studies (e.g. [6][20]). Previous work also supports the use of tracked head-mounted displays over less immersive displays when navigating through an environment. Pausch et al. showed that search tasks could be done more effectively in a head-mounted display when head tracking is used [49]. Additionally, Ruddle et al. showed that navigating large-scale virtual environments was significantly faster in a tracked head-mounted display versus a desktop display [56]. It has also shown that spatial orientation is more consistent in a head-mounted display and the real world than when using a desktop display [42]. All these results point to the effectiveness of using immersive virtual environments for applications involving spatial navigation tasks.

2.1   Studies of Real Walking

Real walking has been shown to support a greater sense of presence and was reported as subjectively easier than walking-in-place and pointing-directed travel [72]. Additionally, 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 [16]. They also reported that participants that used real

walking experienced less motion sickness and scored higher in mental map and basic navigation tests. Ruddle and Lessels also found in two studies that real walking resulted in superior performance over gaze-directed travel on a navigational search task [54] [55]. These results support the general claim that real walking provides benefits over virtual travel techniques.

In a study that attempted to characterize task behavior and performance, Whitton et al. found that that the motions when using walking-in-place or virtual travel do not correlate well with real walking motions [78]. Though real walking is generally considered to be the most natural, realistic travel technique, other research attempting to empirically verify this assumption is sparse. The realism of real walking has also been enhanced by the introduction of passive haptic feedback which allows the user to physically touch objects in the virtual environment [32].

Studies have also previously examined cognitive effects of travel in virtual environments. Jeong et al. found that participants who walked through a real world environment gathered more information than those who explored a virtual world using gaze-directed steering, and attribute this difference to the cognitive difficulty of using the virtual travel technique [36]. However, since real walking in a virtual environment was not included in the study, it is impossible from their data to conclude whether this difference was due to travel technique or differences between the environments.

In a study that specifically investigated travel, Zanbaka et al. found that real walking allowed significantly higher scores on a post-questionnaire involving understanding and higher mental processes, though other information gathering measures

were not significantly different [82]. It is important to note, however, that this experiment evaluated exploratory travel in a single small room which did not require complex maneuvers to navigate. Since previous research has found that the complexity of an environment has a profound impact on navigation tasks [11], it is unclear whether these results will generalize to more complex environments which require more difficult maneuvering.

2.2   Studies of Virtual Travel Techniques

Virtual travel techniques have been the subject of many previous studies. In a study of spatial orientation, Bowman et al. showed that pointing techniques are advantageous to gaze-directed steering techniques for a relative motion task [10]. They also reported that motion techniques that instantly teleport users to new locations are correlated with increased user disorientation. These results point to the advantages of using steering techniques over "magic" techniques for maintaining the user's spatial orientation. In an information gathering experiment, no significant differences were found between gaze-directed, pointing, and torso-directed virtual travel techniques [11]. However, the complexity of the environment was a highly significant factor in determining how much information was gathered from the environment.

Arns et al. investigated different methods of rotation when using several immersive display devices including a head-mounted display, a CAVE, and an immersive workbench [4]. Participants either turned their physical bodies in the direction of travel (gaze-directed steering) or used a handheld device to virtually rotate the world around them while always facing in the same direction. Though no rotation method

consistently outperformed the other on statistical measures, this work suggests that physical rotation techniques are more appropriate for head-mounted displays while virtual rotation may be better suited for CAVE displays.

Additionally, Vidal et. al. compared 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 [74]. This implies that virtual travel techniques may be more effective when they imitate the motions of real walking.

2.3   Other Relevant Work

While locomotion achieved entirely through real walking is now practical for many applications, the size of the virtual environment is ultimately limited by the physical tracking space available. A number of methods have been introduced to overcome this limitation, allowing the use of real walking in virtual environments that are much larger than the physical tracked area. These methods all rely on introducing subtle perceptual illusions which introduce a discrepancy between the physical and virtual walking path of the user. Redirected walking is one such technique that introduces a continuous rotation to guide the user along a modified path through the environment [52]. This method introduces a visual-proprioceptive conflict which has been the subject of several recent studies [25] [62]. Redirected walking has also been combined with passive haptic feedback for objects in the environment to give the user a sense of touch [39]. Alternatively, translational gain techniques have been proposed to increase

the virtual step size of the user without modifying rotation [33] [79].

Other methods have also been proposed which make use of more complicated illusions than manipulating the mapping for rotation or translation. The use of portals which instantly connect two distant environments has also been been presented as a method of overcoming the physical limitation in walking area [15][63]. Additionally, it has been suggested than dynamically modifying the geometry of the environment at runtime could redirect the user's walking path without being noticeable [67]. Peck et al. noted that all these methods can be augmented by introducing reorientation techniques to handle failure cases and showed that visual distractors resulted in less awareness of the reorientation [50].

Given that there has been much recent work involving the exploitation of perceptual illusions to overcome the limitations of the physical tracking area, the evaluation of the real walking technique is all the more important. These illusion-based techniques introduce perceptual conflicts, assuming that the benefits of real walking will outweigh the tradeoffs. However, the benefits of real walking need to be well understood before these techniques can be widely adopted and their use can be justified.

2.4   Summary of Travel Technique Studies

In general, studies of travel have been inconsistent in selecting the travel technique to evaluate, especially among the three virtual steering techniques (see Table 2.1). Gaze-directed travel was the most commonly evaluated technique. However, while 3 out of 9 studies evaluated pointing-directed travel, only one compared the torso-directed technique. These three techniques, though similar in that they rely on parts

Table 2.1: Comparison of previous studies comparing virtual environment travel using [1]real walking, [2]walking-in-place, [3]gaze-directed, [4]pointing-directed, [5]torso-directed, and [6]traditional desktop controls. Selection of technique has been inconsistent across studies, and only one experiment has evaluated the torso-directed technique.

Study	RW^1	WIP^2	GD^3	PD^4	TD^5	$DESK^6$
Bowman et al. [10]			√	√		
Bowman et al. [11]			√	√	√	
Chance et al. [16]	√		√			√
Jeong et al. [36]			√			√
Ruddle and Lessels [54]	√		√			√
Ruddle and Lessels [55]	√		√			√
Usoh et al. [72]	√	√		√		
Whitton et al. [78]	√	√	√			
Zanbaka et al. [82]	√		√			√

of the body to indicate travel direction, provide very different experiences. Yet, only one study has evaluated all three together, and none have compared them all with real walking. Thus, one of the goals of this work were to provide a more thorough evaluation of available steering techniques, which we address in Experiment 3.

The most similar experiment to this work is the study by Zanbaka et al. [82]. However, the environment used by their study was a single room which did not require complicated maneuvers or obstacle avoidance. Since more difficult navigation may be require greater amounts of user attention, the results of their study may not be applicable in those situations. To investigate this question, we expand on this previous work in Experiment 1 by using a virtual maze spread over two floor levels.

Though Whitton et al. showed that virtual travel techniques do not appear to correlate well with real world motions [78], no studies have compared the effects of different virtual environment travel techniques with the real world in the context of cognitive measures such as memory. This is an important research question since

many applications desire a transfer of knowledge from the virtual to real world (such as training systems), and design decisions that interfere with the user's cognitive performance may want to be avoided. In Experiment 2, we created identical virtual and real world environments to investigate these issues.

Other than Zanbaka et al. [82], very few travel technique studies have pre-tested for spatial ability. Spatial abilities may vary greatly between individuals, and are also subject to gender differences [44]. Furthermore, a previous study has found that performance on virtual environment navigation tasks depends not only on the technique, but also on the strategy and sophistication of the user [9]. Thus, all of our experiments included spatial ability pre-tests to explore potential confounding influences on our results.

Information gathering was investigated by several studies and presented as a measurement of relative cognitive difficulty between travel techniques. In Experiment 3, we designed a divided attention task to measure participants' processing capacity while using different travel techniques. We suggest that an attention task is more sensitive and less subject to bias from individual differences in ability than an information gathering task.

CHAPTER 3: EXPERIMENT 1 - MULTI-LEVEL 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. [82]). 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.[1]

3.1   Study 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. **Gaze-Directed (GD):** Participants used a handheld trigger to move forward in the direction determined by the head tracker.

3. **Pointing-Directed (PD):** Participants used the trigger to move forward in the direction determined by a tracker mounted on the handheld device.

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[1]The preliminary results of this study were published in a concise format in the IEEE Symposium on 3D User Interfaces [65]. The final results of this study were also reported in IEEE Transactions on Visualization and Computer Graphics [68].

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.

3.2   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 GD condition, and 15 in the PD 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 pre-test for spatial ability. Additionally, the distribution of these scores was highly uneven across the conditions with 1 in the RW condition, 9 in the GD condition, and 10 in the PD condition. The results from this initial study are reported in Section 3.7.

To correct the problems 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 GD condition; and 12 in the PD condition. A score greater than 5 on the spatial ability pretest was required as an inclusion criteria. During the experiment, only 2 participants did not meet this inclusion criteria and were replaced. Thus, the final corrected results include a total of 51 participants with 17 in each condition. These final results are reported in Section 3.8.

3.3   System Overview

3.3.1   Hardware

Participants wore a Virtual Research VR1280 head-mounted display (HMD), which provided a stereoscopic image with a 60 degree diagonal field of view. Each eye was rendered at a resolution of 1280 x 1024 at 60hz. Audio was provided using the HMD's built-in stereo headphones. We ran the experiment on a Dell Pentium 4 3.0 Ghz PC running Windows XP with 1GB of RAM. Graphics were rendered using an NVIDIA Geforce 6800 graphics card.

For head tracking, we used the 3rdTech Hiball 3100 wide-area tracking system, which provided highly accurate six degree-of-freedom measurements within our 14' x 16' tracking area. One tracker was mounted on top of the HMD to track head position and orientation. To avoid tripping participants while they were walking around, all cables descended from a mounting frame in the ceiling in the center of the tracking area, and the experimenter manually held the cable so it fell directly down the user's back to balance the weight of the HMD.

3.3.2   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 Peripheral Network, which facilitated network communication with the tracking system [70]. Graphics were rendered in software at approximately 55-60 frames per second, and 32-bit spatialized 3D sound was provided using a sampling rate of 44100Hz.

Collision detection was used to prevent the participant from traveling through the walls of the virtual environment. In the event of a collision, the view was rendered from the last valid position prior to entering the virtual geometry. Since the real walking technique requires a direct mapping from physical to virtual viewpoint, this presents a problem for handling collisions. However, we expected collisions with stationary objects while using the real walking technique to be uncommon, and this collision-handling technique was necessary to prevents participants from "cheating" by walking through virtual obstacles. To provide a disincentive for attempting to travel through walls, an audio buzzer was played upon collision with virtual geometry in all conditions.

3.3.3   Experimental Setup

Participants in the real walking condition were allowed to naturally walk through the environment with the position and orientation of their head mapped directly to their virtual viewpoint (Figure 3.1.a). While virtual travel could be accomplished

(a)

(b)

Figure 3.1: (a) When using the real walking technique, participants could naturally walk around about the space. (b) When using a virtual travel technique, physical movement was restricted and travel was accomplished using a device in the dominant hand. Velocity was controlled using a device in the non-dominant hand.

without head tracking, the purpose of this study was to evaluate techniques for immersive head-mounted displays, so head tracking was also used in the virtual travel conditions to provide motion parallax. To simulate the space restrictions typically imposed by a limited-area tracker, the participant stood in the center of a 4' x 4' enclosure constructed from PVC pipe (Figure 3.1.b). Though it was theoretically possible for participants to walk within this restricted area, the fact that participants could not see the barriers while wearing the display and the possibility of collisions served as a disincentive for walking. In practice, we observed that most participants in the virtual travel conditions did not attempt to walk, and instead generally stood in the center of the enclosure and rotated their bodies in a single location.

Figure 3.2 shows the handheld devices used to control virtual travel. For the virtual travel conditions (GD and PD), 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. Translation was restricted to the horizontal plane only, and it was not possible to fly upwards or downwards. Instead, the vertical height was determined by the head position, which allowed participants to bend down to view objects close to the ground.

In the PD condition only, an arrow was rendered on screen at the position and orientation of the user's hand. Since participants could move in 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 non-dominant hand. The

Figure 3.2: The devices used for virtual travel in Experiment 1. Movement was triggered using a button on the tracked device held in the dominant hand. Velocity was controlled using the thumbstick held in the non-dominant hand.

participant manipulated a thumb joystick on this device which acted as a throttle, which was controllable in a range of 0 to 9.84 feet 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. It was not possible for the participants to move backwards.
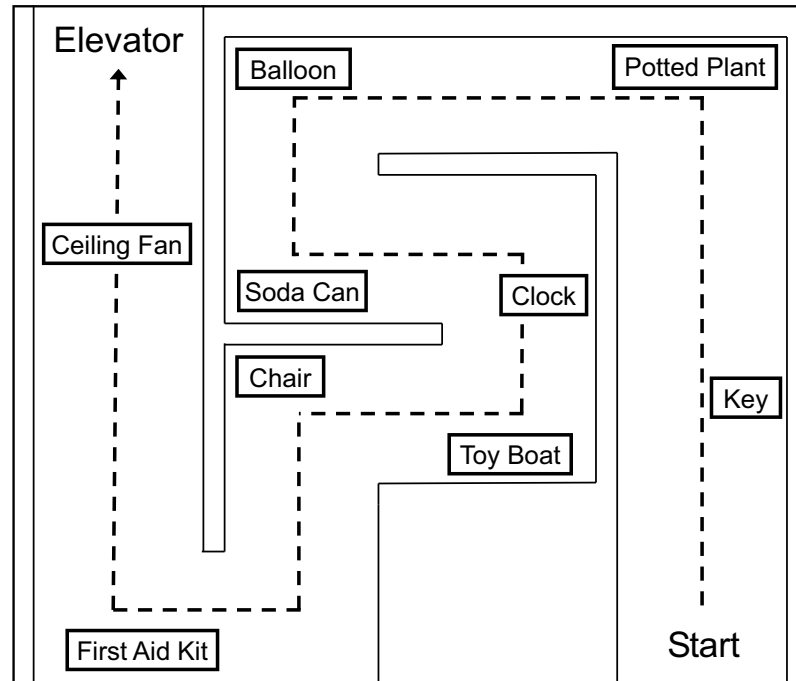
(a) First Floor
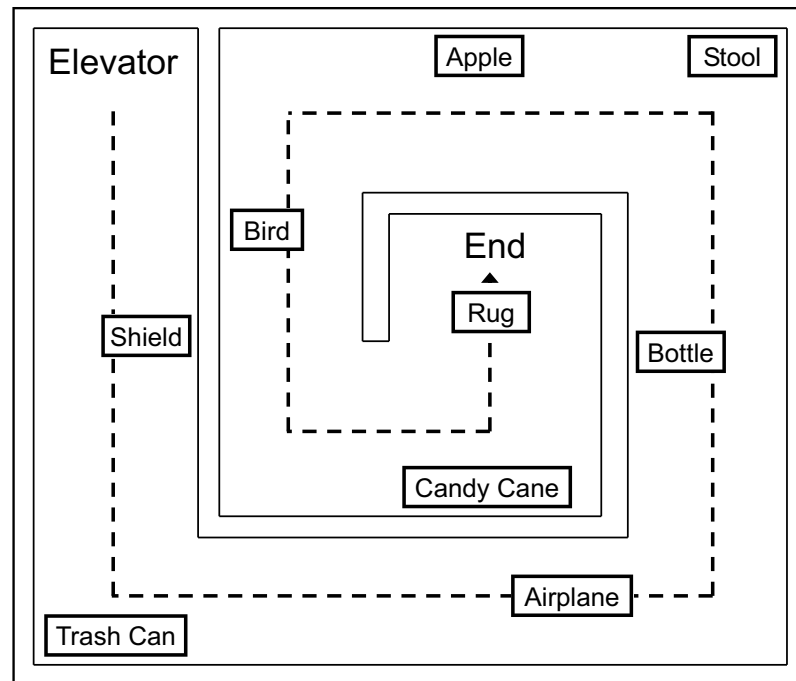
(b) Second Floor

Figure 3.3: (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.
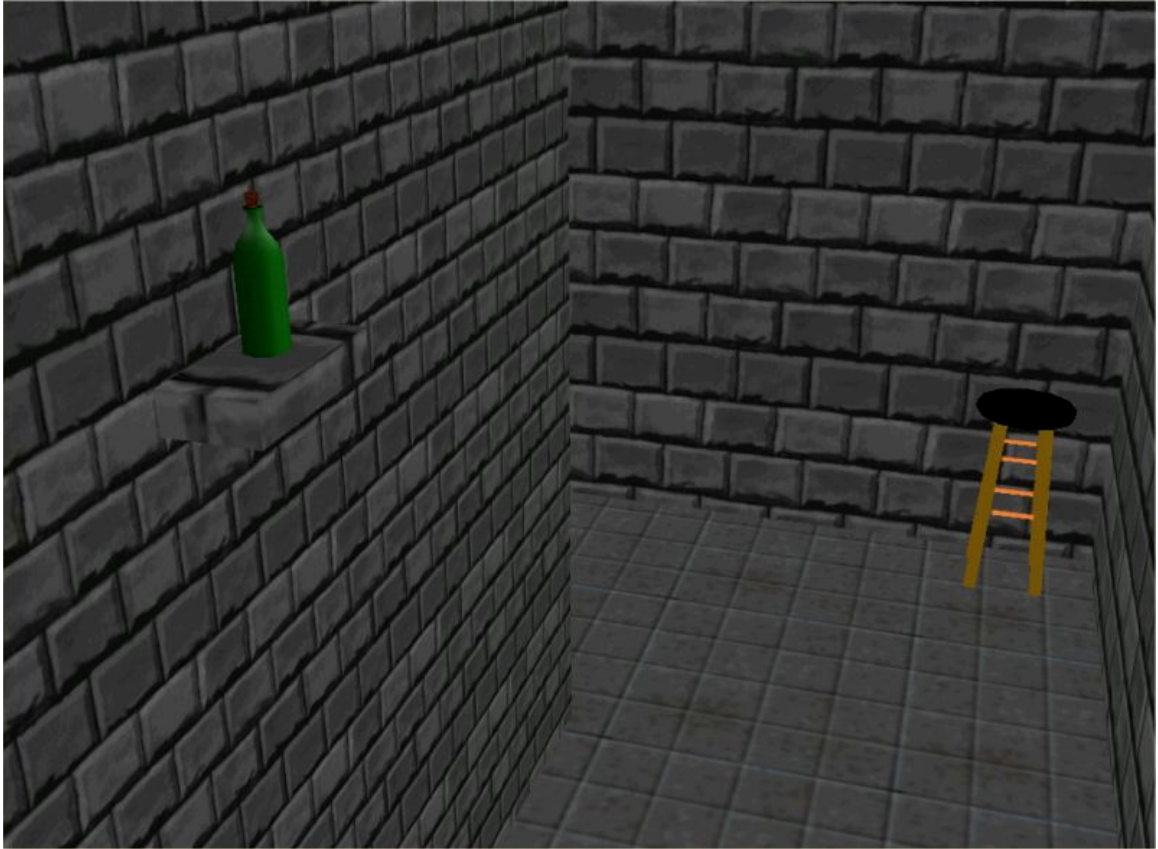
Figure 3.4: A screenshot of the virtual environment used in Experiment 1.

3.4   Virtual 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 (Figure 3.3). The dimensions of the environment were precisely designed to fit our 14' x 16' tracking area, leaving 6-inch borders around the perimeter of the area to avoid collisions with the physical environment. Figure 3.4 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 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.

3.5   Measures

The materials used in this experiment are included in Appendix A.

3.5.1   Simulator Sickness

Simulator sickness was measured using the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [37]. The questionnaire was administered immediately before and after the virtual reality session.

3.5.2   Spatial Ability

Spatial ability was measured using the Guilford-Zimmerman Aptitude Survey Part 5: Spatial Orientation [29]. The test consisted of 60 questions relating to spatial position and orientation with a maximum time limit of 10 minutes.

3.5.3   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.

3.5.4   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 were 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.

3.5.5   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 by [82] and [7]. 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.

3.5.6   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.

3.5.7   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.

3.6   Procedure

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

3.6.1   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.

3.6.2   Experiment Session

The participant was led to the experiment area of the lab 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 GD and PD 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.

3.6.3   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

4. Object Placement

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

3.7   Preliminary Results

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

3.7.1 Simulator Sickness

A 2x3 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 non-significant interaction, $p = .90$. The main effect for SSQ score was not significant, $p = .45$, nor was the main effect for travel technique, $p = .62$. These results indicate reported simulator sickness did not significantly change from before ($M = 13.43$, $SD = 13.04$) to after exposure to the virtual environment ($M = 15.57$, $SD = 17.86$). Additionally, the amount of simulator sickness did not vary across the different travel techniques.

3.7.2 Spatial Ability

Preliminary analysis of the scores indicated that 8 out of 15 participants in the PD condition received nonpositive scores on the test, compared to 1 in the GD 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. Therefore, 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.

The results of the ANOVA were significant, $F(2,37) = 3.73$, $p = .03$, $\eta_p^2 = .17$. Post hoc analysis with the Tukey HSD test revealed that participants in the RW

Table 3.1: 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

condition ($M = 12.18$, $SD = 5.44$) received significantly higher scores than those in the GD condition ($M = 6.89$, $SD = 5.11$), $p = .03$. Participants in the RW condition also scored higher than the PD condition ($M = 9.32$, $SD = 6.82$), but the difference was not significant, $p = .49$. Additionally, the GD and PD conditions were not significantly different, $p = .60$.

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 (Table 3.1). There was a significant positive relationship between spatial ability and object placement, $r(40) = .36$, $p = .02$. All other relationships were not significant. This indicates that we should interpret the results of the object placement test with some caution.

Table 3.2: Mean (SD) preliminary results from the first round of participants in Experiment 1.

	range	RW	GD	PD
Object Recall	*0-18*	7.53 (1.63)	7.24 (2.02)	6.60 (2.59)
Object Recognition	*0-18*	8.81 (3.08)	8.53 (2.60)	7.79 (3.81)
Sketch Maps	*1-5*	2.86 (1.10)	2.71 (0.60)	2.30 (0.46)
Object Placement*	*0-18*	3.29 (2.14)	2.53 (1.91)	1.47 (1.36)
Time*	*sec.*	104.67 (27.21)	137.55 (56.45)	191.01 (85.48)
Collisions*	*count*	0.24 (0.44)	1.65 (3.57)	3.64 (3.43)

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

3.7.3   Post-Tests

Table 3.2 shows the mean results from the post-tests. No significant differences were found between travel techniques for object recall, $p = .45$, or object recognition, $p = .66$. 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, $p = .14$.

The analysis for object placement was significant, $F(2,46) = 3.90$, $p = .03$, $\eta_p^2 = .15$. Post hoc analysis using the Tukey HSD test revealed a significant difference between the RW and PD condition, $p = .02$. The difference between the RW and GD condition was not significant, $p = .46$, nor was the difference between the GD and PD condition, $p = .25$. While this may indicate that the real walking technique facilitated the ability to remember object locations in a complex 3D environment better than the pointing-directed technique, it is important to note that the object placement measure correlated with the spatial ability test. Therefore, we concluded that these results may have been biased by the unequal distribution of spatial orientation across

groups.

3.7.4 Experiment Data

Table 3.2 shows the mean results from the experiment data measures. The analysis for completion time was significant, $F(2, 45) = 8.22$, $p < .01$, $\eta_p^2 = .27$. Post hoc analysis with the Tukey HSD test revealed that participants in the RW condition completed the maze faster than those in the PD condition, $p < .01$, and GD condition, $p = .04$. The RW and GD conditions were not significantly different, $p = .25$.

The results for number of collisions were also significant, $F(2, 45) = 5.58$, $p < .01$, $\eta_p^2 = .20$. Post hoc analysis using the Tukey HSD test revealed that participants in the RW condition experienced fewer collisions with the virtual geometry than those in the PD condition, $p = .14$. However, the number of collisions in the GD condition was not significantly different from the RW condition, $p = .32$, or the PD condition, $p = .14$.

3.8 Final Results

The analysis of the final results from the follow-up study were each treated with a one-way between-subjects analysis of variance (ANOVA) across all conditions with a significance level of $\alpha = .05$ unless otherwise noted.

3.8.1 Simulator Sickness

During preliminary analysis, we identified 1 outlier in the PD 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 2x3 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 non-significant interaction, $p = .87$. The main effect for SSQ score was not significant, $p = .27$, nor was the main effect for travel technique, $p = .43$. 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.

3.8.2   Spatial Ability

The ANOVA indicated that the spatial ability pretest scores were not significantly different across the conditions, $p = .34$. Thus, we can draw more confident conclusions from our final results than we could from our first round of participants.

3.8.3   Post-Tests

Table 3.3 shows the mean results from the post-tests. No significant differences were found between travel techniques for object recall, $p = .65$, or object recognition, $p = .67$. 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, $p = .14$, or object placement, $p = .31$. These results indicate that travel technique did not positively or negatively affect the ability to sketch the maze layout or label object locations.

Table 3.3: Mean (SD) results from the final round of participants in Experiment 1.

	range	RW	GD	PD
Object Recall	*0-18*	7.94 (2.44)	8.12 (2.45)	7.35 (2.64)
Object Recognition	*0-18*	9.50 (3.60)	9.88 (2.96)	8.81 (3.85)
Sketch Maps	*1-5*	2.95 (1.13)	2.79 (0.83)	2.37 (0.56)
Object Placement	*0-18*	3.94 (2.93)	3.29 (2.17)	2.71 (1.69)
Time*	*sec.*	104.80 (28.10)	134.58 (39.12)	184.51 (61.49)
Collisions*	*count*	0.24 (0.44)	0.82 (1.02)	2.35 (2.40)

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

3.8.4 Experiment Data

Table 3.3 shows the mean experiment data results. During the experiment session, 2 participants (1 in the RW condition and 1 in the GD 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, $F(2, 46) = 12.97$, $p < .01$, $\eta_p^2 = .36$. Post hoc analysis with the Tukey HSD test revealed significant differences between the PD condition and the RW ($p < .01$) and GD conditions, $p < .01$. The RW and GD conditions were not significantly different, $p = .16$. 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, $F(2, 48) = 8.75$, $p < .01$, $\eta_p^2 = .27$. Post hoc analysis with the Tukey HSD test revealed significant differences between the PD condition and the RW ($p < .01$) and GD conditions, $p = .01$. The RW and GD conditions were not significantly different, $p = .50$. 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.

3.9   Path Visualizations

Participants' position and head orientation were logged during the experiment session. The tracker data was sampled approximately 15 times per second. This log information allowed us to visualize the paths that each participant took through the virtual environment.

3.9.1   Individual Paths

Figure 3.5 shows sample path visualizations from participants in each condition on each level. Each visualization displays a top-down view of each floor of the environment with a blue overlay indicating the path the participant took through the environment. The brightness of the blue line indicates the length of time each participant spent in a particular location. We can also ascertain relative speed information by examining the distance between the individual sample points that constitute the path.

In comparing individual path visualizations, we observed that participants in the RW condition followed a path that generally remained at a constant speed with few bright spots where they dwelled for longer periods of time. In the GD condition, more bright spots appear along the paths, indicating that participants repeatedly stopped and started moving again. This phenomenon is even more prevalent in the PD condition. In general, the distance between sample points is also greater in the
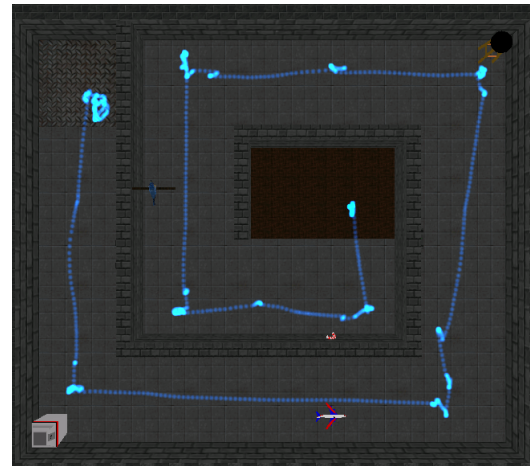
(a) RW Condition - Floor 1
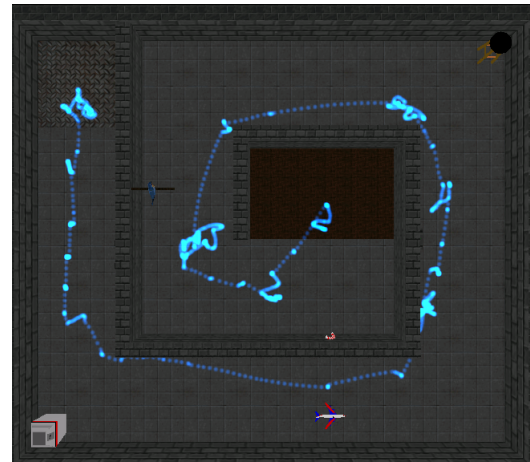

(b) RW Condition - Floor 2

(c) GD Condition - Floor 1

(d) GD Condition - Floor 2

(e) PD Condition - Floor 1

(f) PD Condition - Floor 2

Figure 3.5: Example individual path visualizations for the real walking, gaze-directed, and pointing-directed conditions.

PD condition, which indicates that participants were traveling faster from one point to another. It is interesting to note that despite this observation, participants in the PD condition were the slowest in overall maze completion time. Participants in the GD condition were also slower than those in the RW condition. These factors lead us to believe that the higher speed in the GD and PD condition may have contributed to a loss of control in travelling around corners.

Areas in which participants made many turns in rapid succession are represented in the path visualizations as bright blue clusters. These clusters range in size depending on the number and widths of the turns. In general, the RW condition contained the fewest number of clusters. The GD condition contained more than the RW condition, but the most clusters were present in the PD condition. A larger number of turns in a small area suggests that the participant had trouble maneuvering around corners or that the participant was adjusting the viewpoint in order to observe something in the environment. Since the majority of clusters appear around corners, they are more likely due to the difficulty in maneuvering. This is not a surprising observation, as previous research has suggested that it is more intuitive for participants to travel in their view direction rather than separating the head orientation and direction of movement, as was done in the PD condition [17].

3.9.2   Aggregate Plots

Aggregate plots were generated for each condition by overlaying all of the participants' path visualizations in one display for each level in the environment (Figure 3.6). These visualizations allow us to more clearly observe general movement trends

in the different conditions.

In comparing the aggregate plots of the participants' paths, we observed an interesting pattern in travel for participants in the RW conditions. The non-linear paths are indicative of the sway of the body as the left and right foot alternate. Conversely, the paths in the GD and PD conditions consist primarily of straight line segments. This indicates that the virtual travel conditions do not realistically simulate all the bodily movements associated with real walking.

We also observed that participants in the PD condition took the most direct paths through complex turns in the environment. In a series of multiple rapid turns, these participants would take a direct, straight route without turning, instead of aligning themselves to the specific layout of the hallway. This phenomenon seems slightly less prevalent in the GD condition. However, the plots in the RW condition reveal paths which are aligned more closely with the layout of the turns. The fact that participants were turning less in the virtual travel conditions could explain the larger number of collisions in the PD condition, since this could cause increased difficulty maneuvering around corners.

Since collisions with the walls of the environment were sparse, they were difficult to observe in the individual visualizations. However, collisions become more visible in the aggregate plots. For participants in the GD and PD conditions, the collisions were more common around corners in the environment. The locations of collisions further supports the claim that maneuvering around turns was more difficult in the virtual travel conditions. It is observable in the aggregate plot that participants in the RW condition followed paths through the center of the hallways and, in general,
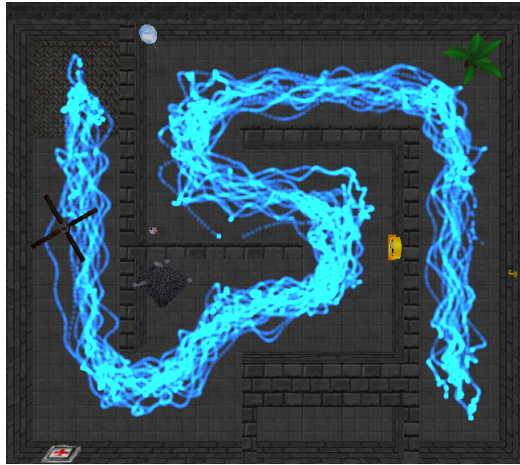
(a) RW Condition - Floor 1
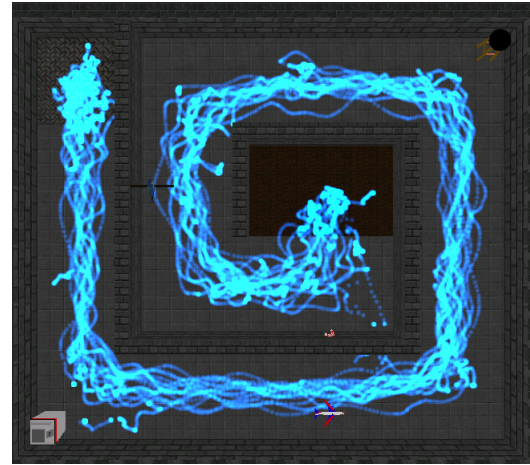
(b) RW Condition - Floor 2

(c) GD Condition - Floor 1
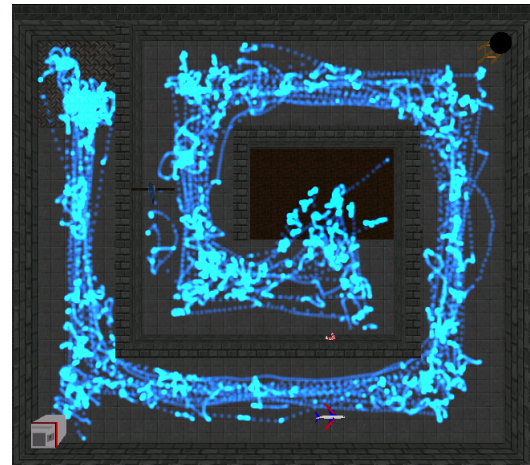
(d) GD Condition - Floor 2
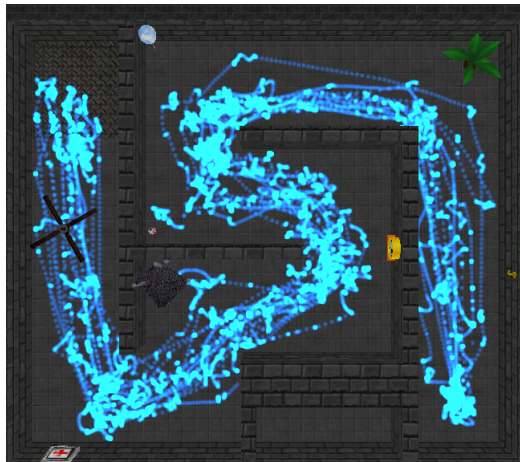
(e) PD Condition - Floor 1
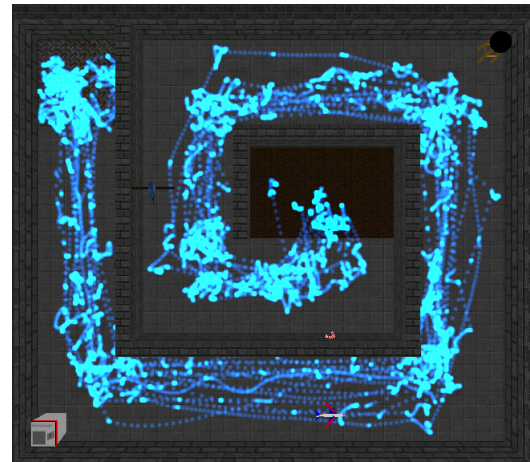
(f) PD Condition - Floor 2

Figure 3.6: Visualization aggregate plots for the real walking, gaze-directed, and pointing-directed conditions.

avoided the walls in the environment.

3.10   Discussion

In our final results, we corrected the uneven distribution of spatial ability which made it difficult to draw concrete conclusions from our first round of participants. We replicated our initial results, with the notable exception of the object placement test. This test was significant in our preliminary results, though we also noted a correlation with the spatial ability scores. Our final results suggest that the uneven distribution of spatial ability had indeed biased the results of this test during the first round of participants.

Participants that used the real walking and the gaze-directed techniques did no worse than those using the pointing-directed 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 pointing-directed technique provides a less efficient method of travel. Additionally, the real walking and gaze-directed 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 pointing-directed technique is more complicated than the other two techniques and may take greater amounts amounts of training to become proficient. Thus, these results may only be applicable to situations where 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 since our environment was considerably more complex then has been previously studied in this context [82]. From this data, we concluded that real walking may not provide cognitive benefits over virtual travel techniques for complex navigation tasks. However, another possible explanation lies in observing that participants using virtual travel conditions took more time to complete the maze. Though navigation was more difficult, these participants had greater time to learn about the contents of the environment. It is also possible that the participants simply reached the limits of their working memory in all techniques, since our results roughly correspond to the "seven plus or minus two" guideline from psychology literature [46]. Thus, there are many possible explanations for the lack of significant results. We attempted to address these open questions, and others, in Experiment 2.

CHAPTER 4: EXPERIMENT 2 - REAL VS. 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.[2] We constructed a complex maze in our tracking area which allowed us to compare navigation in the real world to an identical virtual environment using real walking and virtual travel. The real world condition provides a baseline comparison to determine 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 exists 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 which multiple navigational 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 [61] [76]. Additionally, all participants explored the environment for the same amount of time. This ensured an equal amount of exposure to environment stimuli,

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[2]The results of this study were published in a concise format in IEEE Transactions on Visualization and Computer Graphics [68] and as a poster at IEEE Virtual Reality [69].

since unequal exposure time is one of the confounds we noted in Experiment 1. 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 [22]. Thus, we designed this study to incorporate both visual and auditory information. In addition to a recall test of environment stimuli, we also included a cognition questionnaire related to knowledge, understanding, and reasoning.

4.1   Study Design

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

- **Real World (R):** Participants explored a real world maze.

- **Virtual Environment - Real Walking (VRW):** Participants explored a virtual maze by naturally walking, with their physical position and orientation mapped directly to their position and orientation in the virtual environment.

- **Virtual Environment - Gaze-Directed (VGD):** Participants explored a virtual maze using a gaze-directed virtual travel technique.

In the virtual environment conditions, the real world maze was physically removed from the experiment workspace.

In Experiment 1, we did not find any significant differences between gaze-directed travel and the pointing technique on measures of information gathered during exploration, and gaze-directed travel performed better than pointing-directed in terms of collisions and completion time. As a result, we did not include the pointing technique

in this study.

4.2   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 ($SD = 6.98$).

4.3   System Overview

For this experiment, we used the same equipment as Experiment 1 (see section 3.3 for details). The experiment was run on the same computer hardware, with the exception of the graphics card, which was upgraded to a NVIDIA Geforce 7950 GTX. However, in this experiment, our virtual travel technique did not require hand tracking, so only the PC Ally Airstick was held in the dominant hand. The movement was triggered using a button on the device, and the thumbstick was used to set velocity similarly to Experiment 1. Figure 4.1 shows the experimental setup for this experiment.

4.4   Real and Virtual Environments

4.4.1   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 a large number of turns to navigate through within the 14' x 16' rectangular tracking area.

(a)

(b)

Figure 4.1: (a) When using the real walking technique, participants could naturally walk around about the space. (b) When using the gaze-directed virtual travel technique, physical movement was restricted and travel was accomplished using a handheld device.

A: Audio Object   V: Visual Object   AV: Audio/Visual Object
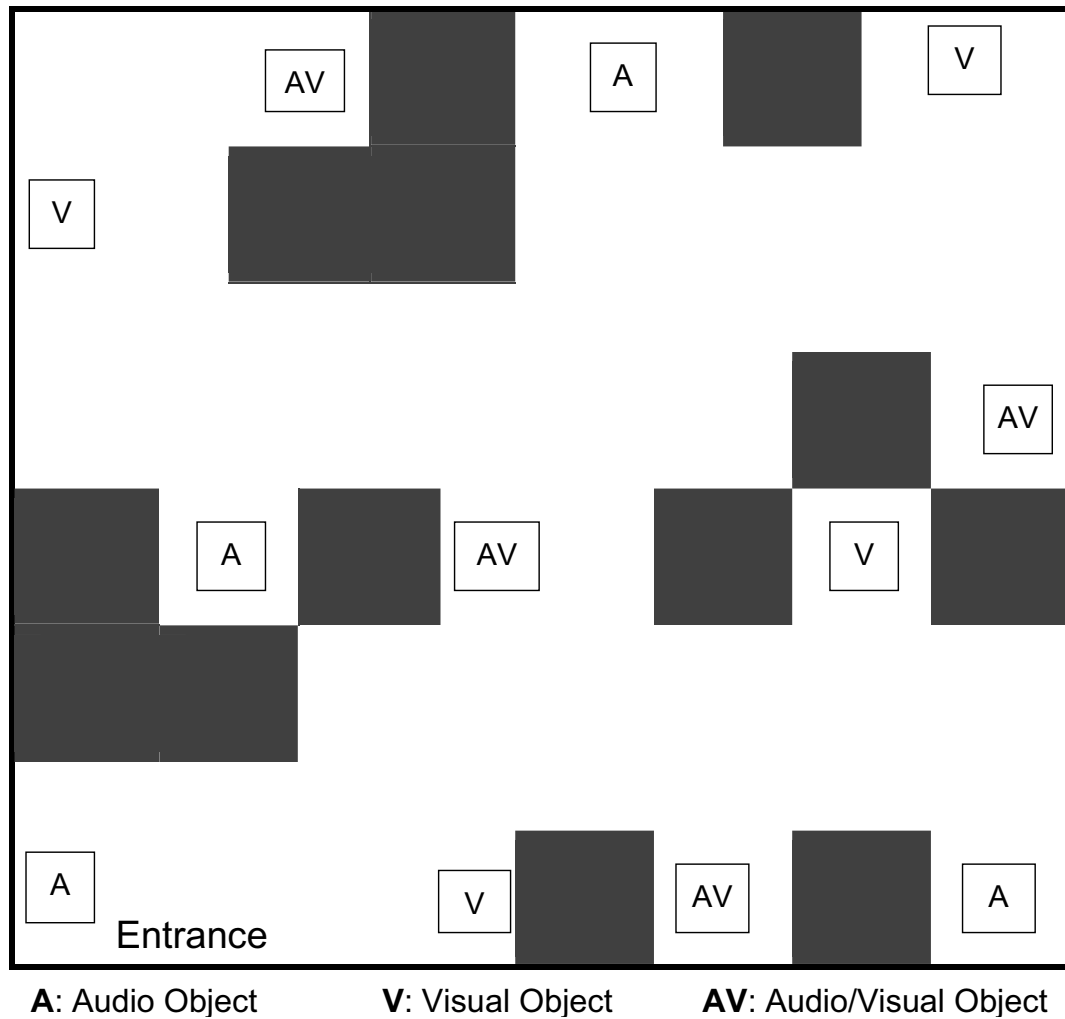
Figure 4.2: A map of the maze layout used to create the real world and virtual environment used in Experiment 2. Dark areas represent barriers that the user had to navigate around. Each box denotes the location of an object.

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

Figure 4.3: A picture of a participant exploring the real world maze used in Experiment 2.

chirping)

- **Audio/Visual (AV):** Pictures with a conceptually matched sound in the same location (e.g. a birthday cake with voices yelling "surprise")

Figure 4.2 shows the layout of the maze and the locations of objects.

4.4.2   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 creating by stacking
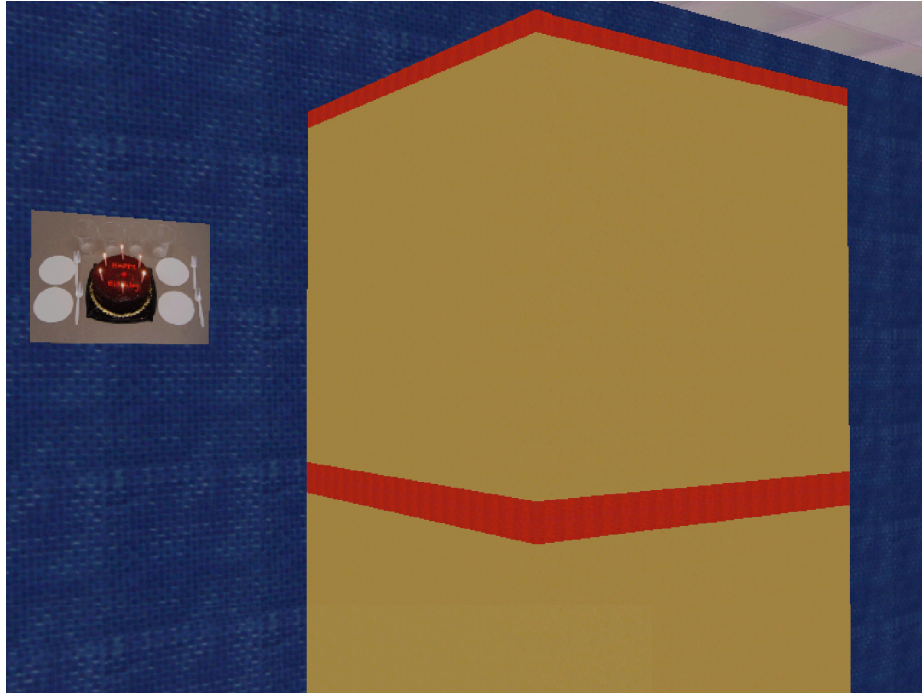
Figure 4.4: A screenshot of the virtual environment used in Experiment 2.

2' x 2' cardboard boxes to form a 2' x 2' x 6' tower which was weighted at the bottom. Figure 4.3 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 faded 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. Figure 4.4 shows a screenshot of the virtual environment.

4.5   Measures

The materials used in this experiment are included in Appendix B.

4.5.1   Pre-tests

Participants were given the same pre-tests for spatial ability and simulator sickness as in Experiment 1. They were also given a questionnaire to collect demographic information. This questionnaire also contained questions related to handedness and computer usage.

4.5.2   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.

4.5.3   Cognition Questionnaire

Participants were given a three part questionnaire to assess cognition, similar to what was done in [82]. 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 [8]. Crooks further condenses these components into three major categories [18]. We developed a set of 24 questions about the environment, each of which correspond 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.

4.5.4   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. There were exactly 12 boxes on the map corresponding to each correct object (no extra boxes were included). 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 were summed to provide a score between 0 and 12.

4.5.5   Experiment Data

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

- Total amount of left and right head turn in degrees

- Total horizontal distance moved in feet

- Total vertical distance moved in feet

- Number of collisions with the geometry of the environment (VRW and VGD conditions only)

4.5.6   Debriefing Questionnaire

Participants were given a debriefing questionnaire which contained five questions corresponding to the following categories:

- Realness of environment

- Clarity of environment (lack of confusion)

- Naturalness of movement

- Ease of movement

- Ease of remembering objects

Each question was phrased as a statement. Answers ranged from 1 to 7 on a Likert scale, with 1 corresponding to 'Strongly disagree' and 7 corresponding to 'Strongly agree.' Responses were recoded so that higher numbers correspond with greater

amounts of the category being measured (for example, a higher confusion score means the participant was more confused). The questionnaire also contained six free response questions to capture qualitative impressions of the experience.

4.6   Procedure

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

4.6.1   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.

4.6.2   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 participants 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 VGD 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.

4.6.3   Post-Experiment

After the experiment session, the participant completed a series of questionnaires in the following order:

1. Post-test for simulator sickness

2. Object recall test

3. Cognition questionnaire

4. Map Placement test

5. Debriefing questionnaire

After completing the questionnaires, the participant was given an opportunity to provide verbal feedback of the experience and ask questions.

4.7   Results

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

4.7.1   Simulator Sickness

A 2x3 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, $F(2,87) = 9.78$, $p < .01$, $\eta_p^2 = .18$. The main effect for time was not significant $p = .45$, nor was the main effect for experiment condition, $p = .18$. These results indicate that simulator sickness varied from before to after instruction differently depending on the experimental condition. Figure 4.5 shows a profile plot for this test.

Paired sample t-tests were conducted to determine individual differences for each condition with a Bonferroni corrected significance value of $\alpha = .017$ to reduce error in multiple comparisons. The most notable result was the VRW condition, in which simulator sickness increased significantly from before to after exposure to the environment, $t(29) = 2.69$, $p = .01$. Simulator sickness in the VGD condition decreased slightly, but this difference was not significant, $p = .66$. Simulator sickness in the R condition, however, decreased significantly, $t(29) = 3.93$, $p < .01$.

Mean Simulator Sickness Results
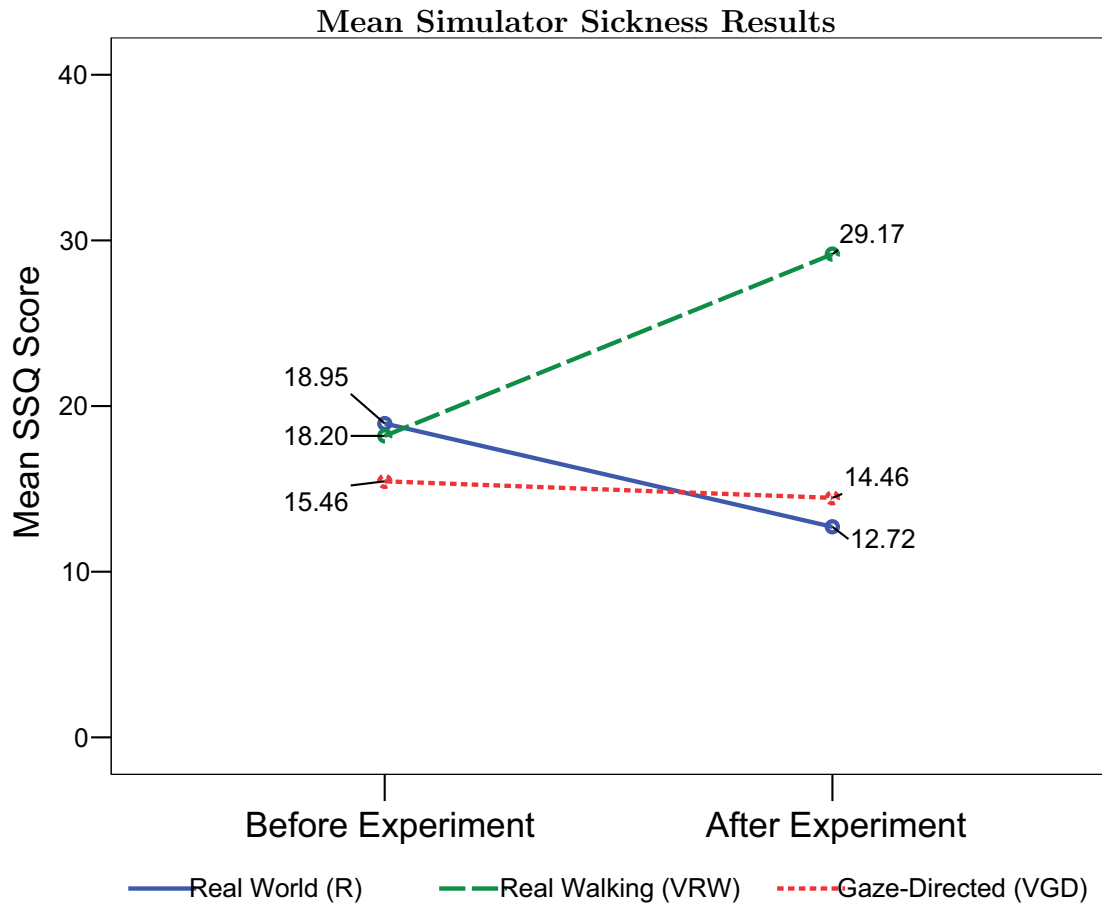
Figure 4.5: Mean SSQ results for Experiment 2. SSQ scores in the VRW condition were greater after the experiment, but decreased in the R and VGD conditions.

4.7.2 Spatial Ability

During preliminary analysis of spatial ability scores, we eliminated one extreme outlier from the data set. The ANOVA was not significant, $p = .35$. These results indicate that, overall, none of the conditions had a significant advantage over another in spatial ability.

4.7.3 Object Recall

The ANOVA for number of objects recalled was significant, $F(2,87) = 23.46$, $p < .01$, $\eta_p^2 = .35$. Post hoc analysis with the Tukey HSD test revealed that participants

Mean Cognition Questionnaire Results
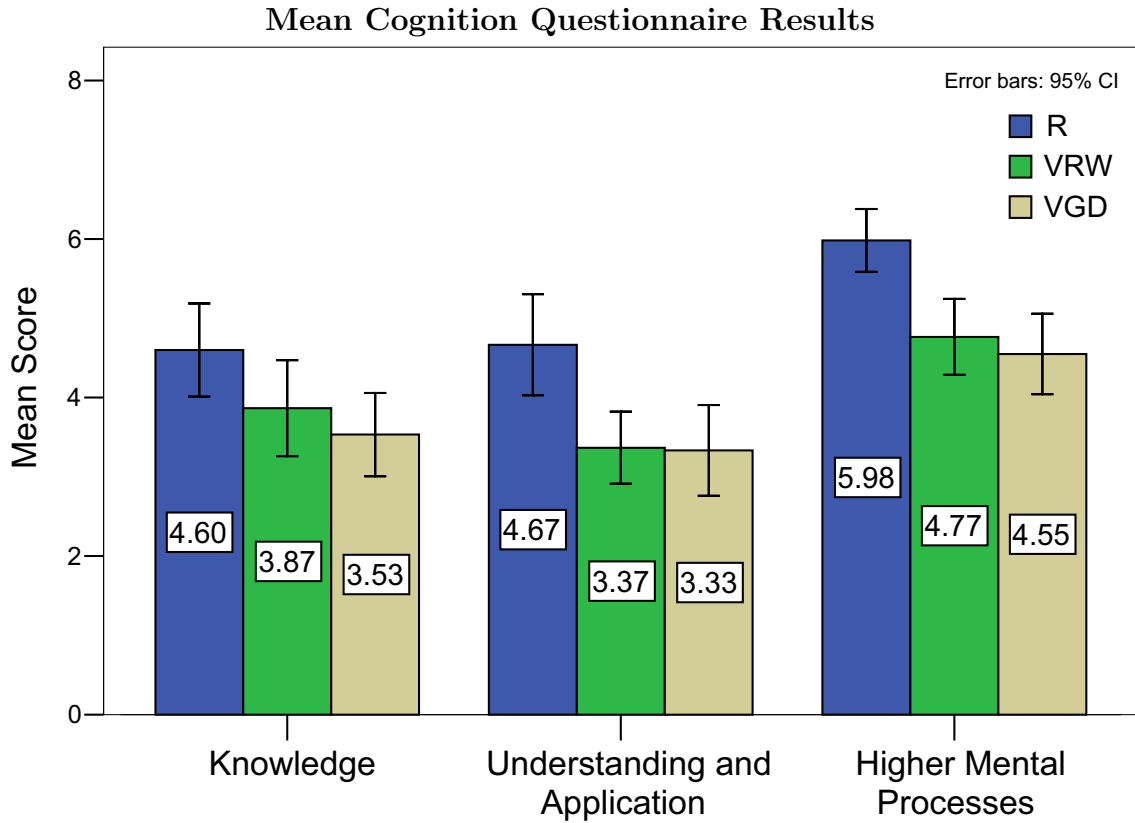
Figure 4.6: Mean scores (between 0 and 8) for the three portions of the cognition questionnaire in Experiment 2. Overall scores were significantly higher in the real world (R condition) than the virtual environment (VRW and VGD conditions).

in the R condition ($M = 8.93$, SD $= .19$) were able to remember more objects those in the VRW condition ($M = 6.40$, SD $= 1.40$), $p < .01$, or the VGD condition ($M = 6.43$, SD $= 1.66$), $p < .01$. The VRW and VGD conditions were not significantly different, $p = .90$, indicating that travel technique in a virtual environment does not appear to significantly influence object recall.

4.7.4   Cognition Questionnaire

Figure 4.6 shows the mean scores across conditions for each of the three cognition measures. A 3x3 mixed ANOVA was performed, testing the between-subjects effect of travel technique and the within-subjects effect of question category (knowledge,

understanding and application, and higher mental processes). The analysis revealed significant main effects for travel technique, $F(2,87) = 11.18$, $p < .01$, $\eta_p^2 = .20$, and question category, $F(2,174) = 38.03$, $p < .01$, $\eta_p^2 = .30$. The interaction was not significant, $p = .63$. Post hoc analysis of the main effect for travel technique with the Tukey HSD test revealed that participants in the R condition received higher scores for all three cognition measures compared to the VRW condition, $p < .01$, and VGD condition, $p < .01$. However, cognition scores were not significantly different between the virtual environment conditions, $p = .78$.

4.7.5   Map Placement

The results for the number of objects placed on the map were significant, $F(2,87)$ $= 33.24$, $p < .01$, $\eta_p^2 = .43$. Post hoc analysis with the Tukey HSD test revealed that participants in the R condition ($M = 9.93$, SD $= 2.61$) were able to correctly place more objects on a map than those in the VRW condition ($M = 4.27$, SD $= 3.22$), $p < .01$, or VGD condition ($M = 4.20$, SD $= 3.49$), $p < .01$. The VRW and VGD conditions were not significantly different, $p = .86$, indicating that travel technique in a virtual environment did not appear to significantly influence map placement.

4.7.6   Collisions

We performed an independent samples t-test to analyze collisions in the VRW and VGD conditions only, since it was not sensible to calculate collisions with virtual geometry in the R condition. Participants in the VRW condition experienced fewer collisions ($M = 3.50$, $SD = 3.32$) than participants in the VGD condition ($M = 5.73$, $SD = 3.97$), $t(58) = 2.37$, $p = .02$. These results indicate that it is more difficult to

avoid collisions with the virtual geometry when using a gaze-directed virtual travel technique instead of real walking.

4.7.7   Distance Covered

The ANOVA for horizontal distance covered (in feet) was significant, $F(2,87) = 34.14$, $p < .01$, $\eta_p^2 = .44$. Post hoc analysis with the Tukey HSD test revealed that participants in the R condition ($M = 322.67$, $SD = 68.31$) covered more horizontal distance than participants in the VRW condition ($M = 248.26$, $SD = 54.20$), $p < .01$, or VGD condition ($M = 197.70$, $SD = 53.02$), $p < .01$. The horizontal distance covered in the VRW condition was also significantly greater than the VGD condition, $p = .04$. These results indicate that participants that explored the real environment walked the greatest distance in a set amount of time. Additionally, participants in the gaze-directed condition moved the least out of all the conditions.

The analysis for vertical distance covered (in feet) was also significant, $F(2,87) = 28.76$, $p < .01$, $\eta_p^2 = .40$. The post hoc analysis revealed that participants in the R condition ($M = 35.30$, $SD = 12.80$) covered more vertical distance than participants in the VRW condition ($M = 28.48$, $SD = 11.65$), $p = .04$, or VGD condition ($M = 14.99$, $SD = 5.94$), $p < .01$. The vertical distance covered in the VRW condition was also significantly greater than the VGD condition, $p < .01$. 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.

4.7.8   Head Turn

A 2x3 mixed ANOVA was performed on total amount of head turn (in degrees), 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, $F(2,87) = 6.63$, $p < .01$. The main effect for experiment condition was also significant, $F(2,87) = 19.48$, $p < .01$. There was also a significant main effect for direction of head turn, $F(1,87) = 21.71$, $p < .01$. 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 of the between-subjects main effect of experimental condition using the Tukey HSD test revealed that the amount of head rotation in the R condition was greater than the VRW condition, $p < .01$, and the VGD condition, $p < .01$. 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, the VRW condition and VGD condition were not significantly different, $p = .33$, indicating that travel technique in the virtual environment conditions does not appear to influence the total amount of head turn.

Figure 4.7 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 VGD condition only tended to heavily favor turning towards the left. This difference between left and right head turn in this condition was
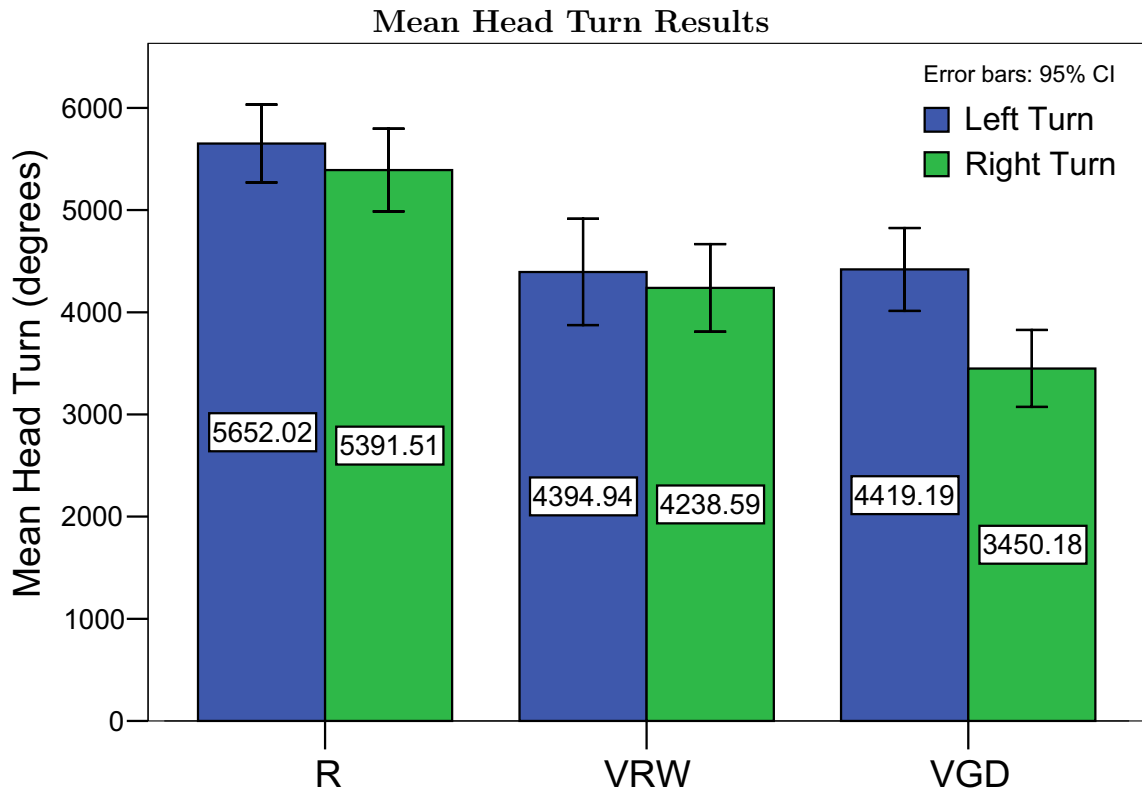
Figure 4.7: Mean head turn results by direction (in total degrees turned). Participants in the VGD condition tended to favor left turns over right, while turns in the other conditions were roughly even.

significant, $t(29) = 6.42$, $p < .01$. Moreover, this trend was very noticeable during the experiment session; many participants in the VGD 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.

4.7.9 Debriefing Questionnaire

Figure 4.8 shows the mean results across conditions for each of the five questions, rated on a 7-point Likert scale. A 3x5 mixed ANOVA was performed, testing the between-subjects effect of travel technique and the within-subjects effect of question
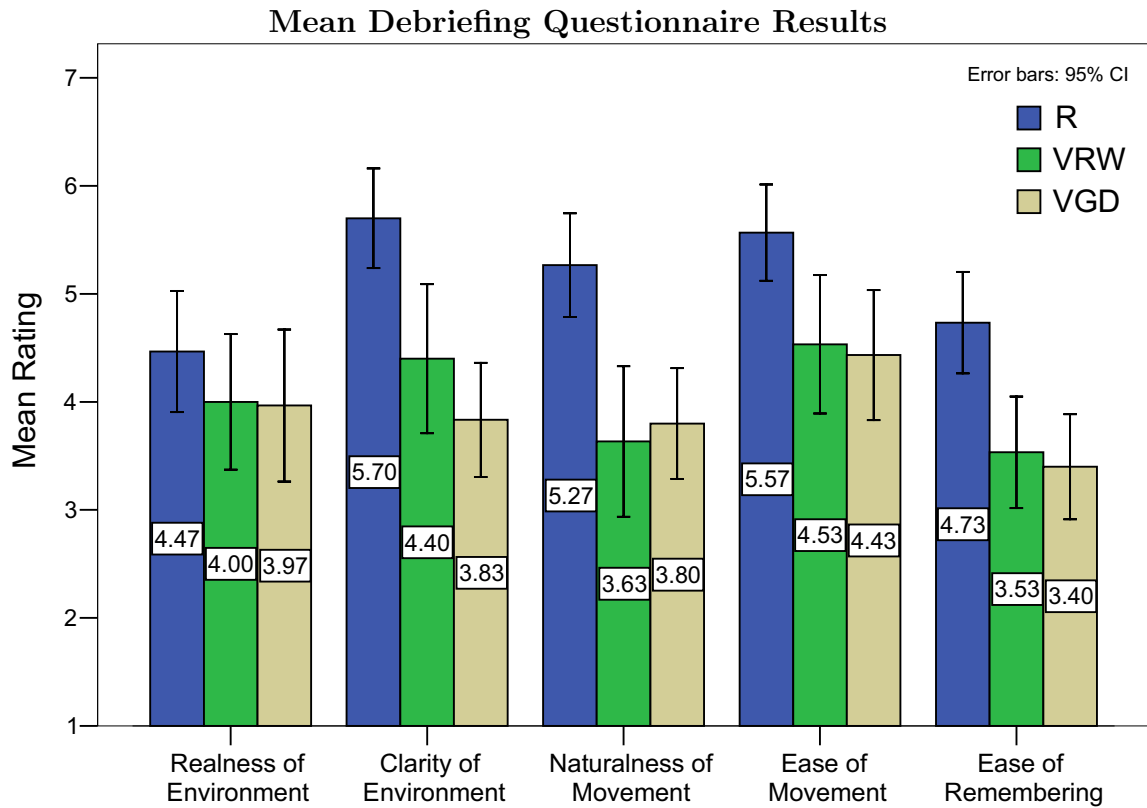
Figure 4.8: Mean results of the debriefing questionnaire ratings (on a 7-point Likert scale). Overall ratings were significantly higher in the real world (R condition) than the virtual environment (VRW and VGD conditions).

category (realness of environment, clarity of environment, naturalness of movement, ease of movement, and ease of remembering objects). The analysis revealed significant main effects for travel technique, $F(2,87) = 17.08$, $p < .01$, $\eta_p^2 = .28$, and question category, $F(4,348) = 7.31$, $p < .01$, $\eta_p^2 = .08$. The interaction was not significant, $p = .21$, indicating that travel technique did not cause the ratings to vary significantly between the different debriefing questions. Post hoc analysis of the main effect for travel technique with the Tukey HSD test revealed that participants in the R condition gave higher overall ratings than those in the VRW condition, $p < .01$, and VGD condition, $p < .01$. However, overall debriefing ratings were not significantly different

between the virtual environment conditions, $p = .84$.

4.7.10   Qualitative Comments

Review of the free response questions on the debriefing questionnaire yielded a number of interesting qualitative comments. Many participants indicated that the real walking technique was intuitive, and contributed to the realism of the environment. For example:

- "It was nice to have real ranges of motion." (VRW)

- "It really did seem like I was in a maze." (VRW)

Many of the participants in this condition, however, expressed desire to have an alternative method of moving in the virtual environment. Surprisingly, the addition of a joystick to the system was a common suggestion. These comments often mentioned experience with video games. For example:

- "I love video games, so being able to move around with a controller or mouse would have been a lot more natural." (VRW)

- "If I had been sitting down or had a joystick to move with, exploring would have been a lot easier." (VRW)

Comments about the VGD condition were also mixed. Some participants found the travel technique intuitive, while others expressed that they would have preferred the real walking technique. Examples of participant comments include:

- "The joystick was very easy to operate." (VGD)

- "A lot of turns were required, and turning was really difficult." (VGD)

- "I would have done much better if I could just walk. I spent more time trying to figure out the remote than memorizing objects." (VGD)

4.8   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 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 [43]. Also, with reduced field of view, participants can see less of the environment at any given time, which may have reduced the amount of stimuli observed and encoded in memory. The HMD also increases weight and inertia on the head, which has been known to cause fatigue and motion sickness [23]. Additionally, visual differences between environments may have played a role, though a similar study did not find that differences in visual detail influenced navigation [54].

In spite of the differences between the real world and virtual environment, our data indicated no significant differences between real walking and gaze-directed travel on the recall test, map placement test, or cognition questionnaire. These results are important for applications where supporting memory or cognition is an important goal. It is also interesting to note that there no significant differences between real

walking and gaze-directed travel on our debriefing ratings, especially naturalness and ease of movement. Additionally, responses from the qualitative questionnaire were mixed, indicating that some participants wanted to walk, and others would prefer to use virtual travel. These point to the importance of considering the expertise and goals of the target population when designing travel for virtual environments. However, in general, our findings from this study suggest that for complex virtual environments where supporting memory and learning is an important goal, the gaze-directed travel technique may be substituted as a less expensive alternative to real walking.

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 [82] or lesser motion sickness when using real walking [16]. 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 gaze-directed travel condition tended to turn about in a stationary location, and on average this behavior did not appear to induce

simulator sickness. This suggests that gaze-directed travel may actually be a better choice for reducing simulator sickness in environments requiring a great amount of physical maneuvering, especially as the amount of time immersed in the environment increases.

The testing effect is one possible explanation for the decrease in simulator sickness after exploration in the R condition, and we suggest that the re-testing of the same questionnaire biased the participants towards lower scores on the second test. This explanation seems likely since we have no other reason to believe participants in the R condition would have experienced any difference in symptoms from before to after the experiment. Additionally, testing effects for this questionnaire have been noted in previous work [81]. Given the trend towards lower post-test scores in the other conditions, this makes the rise in simulator sickness in the VRW condition alarming.

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 gaze-directed 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 be less likely to 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 supports the claim that real walking results in navigational behavior that is more similar to the real world than virtual travel.

We also observed differences during the experiment in participants' explorations of

tight areas of the environment. Participants that used the gaze-directed travel technique seemed more cautious about fully exploring the dead ends in the maze than walkers in the virtual environment. Given that the study allowed free exploration, participants may have adopted different wayfinding strategies based on the available travel technique or their individual abilities. These individual strategies may have subsequently influenced our measurements of gathered information about stimuli observed during exploration. We addressed these potential confounds in Experiment 3.

CHAPTER 5: EXPERIMENT 3 - DIVIDED ATTENTION TASK

Based on the results of the first two experiments, we conducted Experiment 3 to probe some of the open questions raised during these studies.[3] In addition, to provide a comprehensive comparison of real walking and virtual steering techniques, we expanded our evaluation to include real walking, gaze-directed, pointing-directed, and torso-directed travel. The experimental task was also carefully designed to provide a more sensitive measurement of the cognitive difficulty of navigation. Participants were required to divide their attention between two simultaneous tasks: a navigation task which required pursuit of a moving target and an attention task to measure participant's spare processing capacity.

In addition to our first two experiments, information gathering measures have been used by many previous studies [11] [36] [82]. However, we suggest they may not be sensitive enough measurements of cognitive processing due to a number of confounding factors. These types of measurements could be highly influenced by individual differences in wayfinding strategy and user proficiency, which we observed can vary greatly from person to person. Furthermore, a previous study has also found that performance on virtual environment navigation tasks depends not only on the technique, but also on the strategy and sophistication of the user [9]. More specifically,

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[3]The results of this study will appear in a concise format in the IEEE Symposium on 3D User Interfaces [66].

the resulting differences in the participants' explorations of the environment could result in each participant seeing different stimuli for varying amounts of time. To remedy this problem, our attention task consistently presented stimuli auditorily as the participant moved through the environment. Additionally, the navigation task was designed as pursuit of a visible moving target instead of free exploration to reduce effects of different wayfinding strategies as much as possible. Thus, subsequent memory tests of the stimuli will be less subject to bias from individual differences in navigation between participants. Performance on the attention task also provided additional measurements of cognitive processing capacity that were not based on memory of stimulus events.

We also investigated gender effects, since they have been shown to be a strong determining factor of performance on spatial tasks [75]. Numerous studies have provided evidence for gender differences in spatial abilities and strategies. For example, a study comparing spatial updating by self-motion and landmark-based orientation revealed gender differences in higher level strategies for spatial orientation [41]. Recent work has also investigated gender differences in abilities to discriminate between real and virtual motions [14]. However, in the context of immersive virtual environment travel techniques, gender effects have not been sufficiently explored, and may be a discriminating factor on the performance of experimental tasks.

Additionally, we explored several other criteria that could account for differences in navigation tasks. Several studies have found that complexity of the environment, and subsequently, difficulty of travel, is an important factor on the performance of navigation tasks [9] [11]. Therefore, we designed two levels of difficulty for our spatial

navigation task. We also expanded our spatial ability measures to include two common pen-and-paper tests, along with an immersive virtual reality spatial orientation test, in order to explore potential confounds of our results.

5.1   Study Design

The study used a mixed design with participants randomly assigned to one of the following four between-subjects **travel conditions**:

1. **Real Walking (RW)**: Participants traveled through the environment by walking naturally. Their physical position was mapped directly to their virtual position.

2. **Gaze-Directed (GD)**: Participants used a handheld controller for locomotion. The movement direction was determined by the direction of their head.

3. **Pointing-Directed (PD)**: Participants used a handheld controller for locomotion. The movement direction was determined by the direction of their hand.

4. **Torso-Directed (TD)**: Participants used a handheld controller for locomotion. The movement direction was determined by the direction of their torso.

We also investigated **gender** as a between-subjects variable. Each subject experienced four separate trials in the virtual environment, corresponding to different combinations of the within-subjects variables of **task difficulty** (simple or complex) and **task type** (single task or divided task). To remove ordering effects, the order of the trials were balanced across the conditions using a Latin Squares design.

We hypothesized that real walking would allow superior performance over some of the virtual travel techniques, most notably pointing-directed travel, on a divided attention task. We also hypothesized that gender and task difficulty would be discriminating factors in performance.

5.2   Participants

A total of 128 people participated in the study (45 male, 83 female) with 32 participants in each travel condition. Participants were evenly distributed across the travel conditions with respect to gender, with 11 males and 21 females per condition. The mean age of participants was 20.78 ($SD = 5.62$). They were primarily recruited from an undergraduate general psychology course, and were offered a research credit for participating. Participants were required to have normal or corrected-to-normal vision, use of at least one hand, good hearing, and the ability to communicate comfortably in spoken and written English.

5.3   Virtual Environment

The virtual environment was designed as an empty room with six columns placed to form a grid of corridors (see Figure 5.1). The columns were placed as obstacles in order to force participants to navigate around sharp turns. The environment was designed precisely to fit within the 14' x 16' tracking area. Depending on the trial, participants were instructed to either perform the primary task alone or a divided attention task (consisting of both the primary and secondary tasks) in the virtual environment. Each of the four trials lasted for 115 seconds.
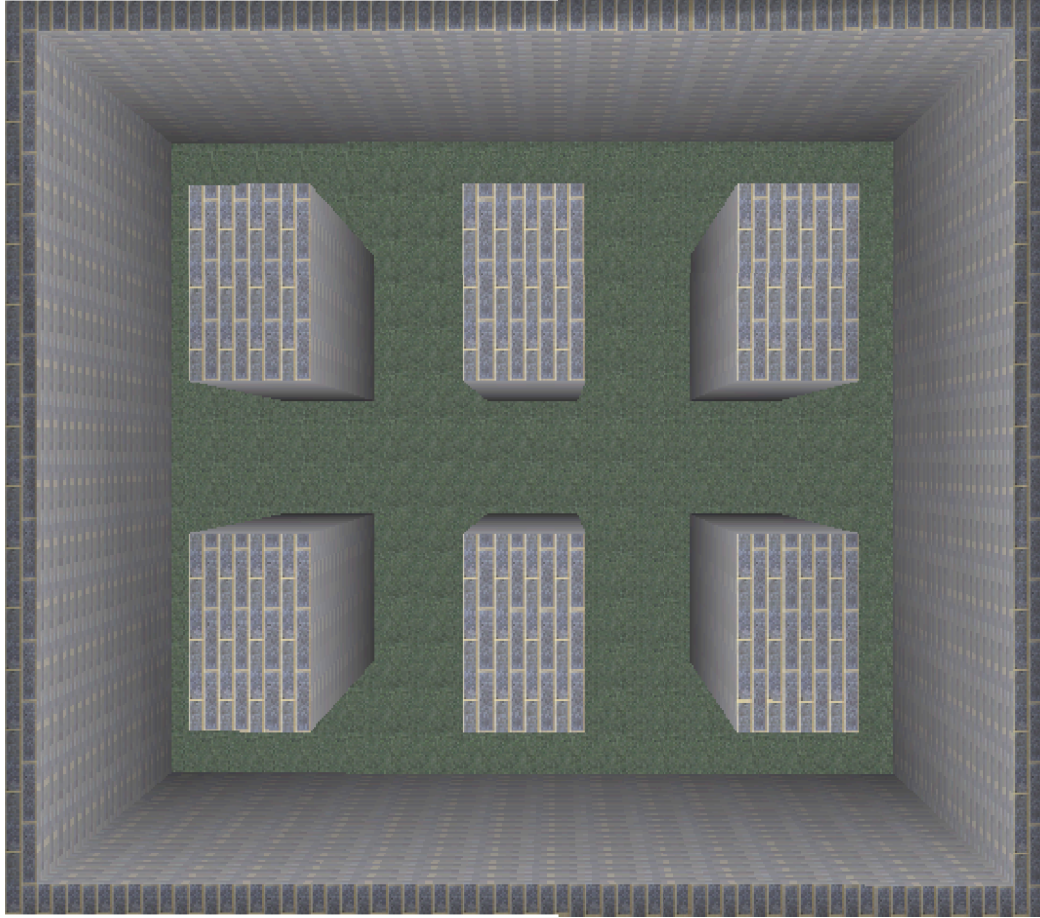
Figure 5.1: A top-down view of the virtual environment used in this study.

5.3.1   Primary Navigation Task

The participants were told that their primary task was to follow a moving red sphere through the environment as closely as possible. This was designed as a guided navigation task in order to focus on investigating the effects of travel technique on physical locomotion and avoid introducing bias from individual differences in wayfinding strategy. The sphere was rendered at eye level and moved at a speed of 18 inches per second. It moved in a straight line and made 90 degree turns around the columns, which forced participants to stay close to the object to keep it in view. We designed two levels of difficulty through pilot testing, which we describe as simple and complex

difficulty (relative to each other). For the trials of simple task difficulty, the sphere performed 18 turns; for the trials of complex task difficulty, it turned twice as often, performing a total of 36 turns. This task allowed us to measure how well participants were able to navigate around obstacles and follow the target as this process became more taxing.

5.3.2   Secondary Attention Task

In two of the trials, participants performed only the primary navigation task. In the other two trials, participants were also told to perform a simultaneous secondary task as they followed the target sphere through the environment. For the secondary task, a word was played through the headphones every five seconds, and participants were instructed before beginning to listen for words that fit a specific conceptual category. The participant was told to press a button on their handheld controller when they heard a category word. Distractor words were also played, and the participants were instructed to ignore them. The performance on this attention task allowed us to compare the amount of spare mental resources during the primary navigation task. Participants were specifically told that following the target sphere was the more important task.

The attention task was implemented using audio for two reasons. First, since traveling in a virtual environment is a visual task, audio provides an input channel which would not interfere with their primary task. Second, since the words are presented auditorily at regular intervals, we ensure that exposure to the stimuli is consistent for each participant.

For the two experiment trials which included the secondary task, two categories were selected: parts of a house and parts of the body. These words were originally selected from the Murdock categorized word pool [48]. From the original 32-word lists, we eliminated 10 words from each list that were either too lengthy (greater than two syllables) or were extreme outliers in word frequency according to the Kucera and Francis word pool [27]. We then divided each list in half, evenly balancing number of syllables and word frequencies as much as possible, forming four lists of 11 words each. Four lists of 11 randomly selected distractor words were also constructed with balanced word frequencies that approximately matched the category word lists. For each trial in the experiment, a list of category words and distractors was presented in random order. The order of the lists selected for the trials were balanced across the entire study to remove order effects introduced by individual differences in the word lists.

5.4   System Overview

For this experiment, we used the same head-mounted display, tracking system, and physical enclosure as Experiment 1 (see section 3.3 for details). However, in the torso-directed condition, it was also necessary to track the orientation of a participant's torso independently of the head. Thus, participants wore a small nylon gym bag with a lightweight cardboard frame inside to provide a mounting point for a second Hiball tracker. While this was only necessary for this condition, this backpack was worn in all conditions to provide a consistent level of encumbrance across the experiment conditions. Figure 5.2 shows the equipment used during the study.

| (a) RW Condition | (b) GD Condition | (c) PD Condition | (d) TD Condition |
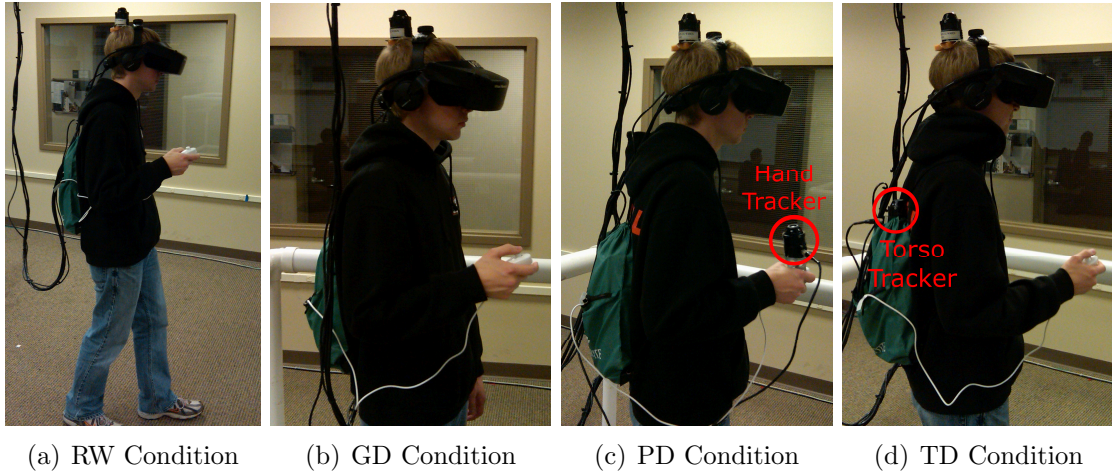
Figure 5.2: (a) When using the real walking technique, participants could naturally walk about the space. (b-d) For the gaze-directed, pointing-directed, and torso-directed techniques, physical movement was restricted and movement was controlled using a handheld joystick.

For user input, participants held a Nintendo Wii Nunchuk controller in their dominant hand. The Nunchuk was connected with a wire to a Nintendo Wiimote controller in the user's backpack, which in turn reported input events wirelessly over Bluetooth. In the pointing-directed condition, it was also necessary to track the orientation of the user's hand. While the Nunchuk has built-in accelerometers for motion sensing, it lacks a gyroscope, and as such is not sufficient to provide three degree-of-freedom tracking. To achieve this, we added a mounting frame for the Hi-ball tracker to the Nunchuk. Participants in the pointing-directed condition used this modified Nunchuk/Hiball controller, and all other participants used an unmodified one. Although the modified controller is heavier than the controller used in the other conditions, we do not believe this will impact our results since the position of the hand in the other conditions is not relevant to the study.

Travel and collision detection were treated similarly to Experiment 1, except for

a notable difference in controlling virtual movement and velocity control. One advantage of using the Nintendo Wii Nunchuk controller is that it provides an elastic thumb stick, which allows the movement trigger and velocity control to be combined. Participants were capable of moving both backwards and forwards by pushing the thumb stick in the appropriate direction, and velocity was elastically controllable along a continuous spectrum from 0 to 3 feet per second. Similar to Experiment 1, an arrow was rendered at the position and orientation of the participant's hand to provide visual feedback of the travel direction in the pointing-directed condition.

The experiment was run on a Dell Pentium 4 3.4 GHz PC running Windows XP with 2 GB of RAM and an NVIDIA Quadro FX 4500 graphics card. The virtual environment was implemented using OpenSceneGraph 2.8.0 with graphics rendered at 60 frames per second and audio provided through OpenAL. Tracker communication was accomplished using the Virtual Reality Peripheral Network [70]. For reading input events from the Nintendo Wiimote, we used the WiiYourself! library [1].

5.5   Measures

The materials used in this experiment are included in Appendix C.

5.5.2   Task Performance Measures

To measure performance on the primary navigation and secondary attention tasks, we collected the following data:

- **Target distance**: The average distance between the participant's viewpoint and the target sphere in inches was recorded for each of the four trials. This measurement indicates how well participants were able to perform the primary

navigation task by following the sphere.

- **Response score**: The response score was calculated for each of the two divided task trials by subtracting the percentage of false alarms (responding to distractors) from the percentage of hits (responding to category words) to correct for guessing. This indicates how well participants were able to perform the secondary attention task.

- **Response time**: The average time in seconds for correct button presses after hearing a word was recorded for each of the two divided task trials.

Movement data from the head tracker and virtual camera were also logged to record the participant's performance on the navigation task. The data from the hand/torso tracker, however, was not recorded.

5.5.1 Word Recognition Test

Participants were given a computerized word recognition test after each of the two experiment trials where the divided task were performed. To avoid the recency effect, which would allow them to automatically recite the last words heard from their working memory, participants were instructed to count backwards from 50 down to 0 prior to starting the test. They were presented with a total of 44 words one at a time in random order, and were asked if to indicate if the word was played during the experiment. The list consisted of an equal number of old (played during the experiment) and new (not played during the experiment) category and distractor words. The participant responded "yes" or "no", and was then asked to rate their

confidence on a scale from 1 (not very confident) to 3 (very confident). To calculate the word recognition score, the percentage of false alarms (incorrectly responding "yes" to a new word) was subtracted from the percentage of hits (correctly responding "yes" an old word) to correct for guessing. The confidence ratings for old words were combined to provide a 6-point scale (1 = very confident no, 2 = somewhat confident no, 3 = not very confident no, 4 = not very confident yes, 5 = somewhat confident yes, 6 = very confident yes) [26]. The confidence score was calculated as an average of these ratings.

5.5.2   Simulator Sickness Questionnaire

As travel technique has been previously noted to have an impact on simulator sickness, this is an important phenomenon to measure. We used the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) to measure the change in simulator sickness before and after the experimental session [37].

5.5.3   Spatial Ability Pre-Tests

We used several tests to evaluate spatial ability. Participants took the Vandenberg & Kuse Mental Rotations Test (Redrawn Version) [51] and the Guilford-Zimmerman Aptitude Survey Part 5: Spatial Orientation [29]. The Vandenberg & Kuse test was administered in 8 minutes and yielded a score between 0 and 24. The Guilford-Zimmerman test was shortened to 36 questions administered in 5 minutes [47]. It yielded a score between -9 and 36. In both tests, higher scores corresponded to better performance.

During the first two experiments, we observed that some participants struggled and

expressed dissatisfaction with the Guilford-Zimmerman test, and we considered that pen-and-paper spatial tests may not be always earnestly attempted because some participants may find them difficult and tedious. Thus, in addition to the pen-and-paper tests, we also administered a virtual reality spatial orientation test. Participants wore the head-mounted display and were placed in a 3D grid of corridors. They were moved through four series of turns in random directions, then asked to point back to the direction of their start location. They were given one practice attempt, followed by five actual trials. The test took approximately three minutes. The measurement from this test was the average angular difference between their point direction and the direction of their actual starting location across all five trials (between 0 and 180), with a lower angle corresponding to better performance.

5.5.4   Video Game Experience

We included several questions on a demographic survey to measure experience with video games and 3D environments. Participants were asked to select how many hours they spend playing video games in an average week from the following choices (in hours): 0-3, 4-7, 8-11, 12-15, 16-19, 20 or more. These responses were coded on a scale from 1-6, with higher numbers corresponding to more hours. Participants were also asked to rate their experience with games that take place in a 3D environment on the following scale: not experienced at all, a little experienced, experienced, very experienced. These responses were coded on a scale from 1-4, with higher numbers corresponding to greater experience.

5.6   Procedure

The experiment was conducted one participant at a time, and took each participant approximately one hour to complete.

5.6.1   Pre-Experiment

The participants first read an information sheet describing the study in detail. After being given an opportunity to ask questions, they then read and signed the informed consent form. After consent had been obtained, the participants completed the following: (1) a demographic survey, (2) the Vandenberg & Kuse spatial ability test, (3) the Guilford-Zimmerman spatial ability test, (4) the simulator sickness pre-test, and (5) the virtual reality spatial ability test.

5.6.2   Experimental Session

After completing the pre-tests, the participants were shown how to travel in the virtual environment and operate the handheld controllers (if applicable). Prior to entering the experiment virtual environment, the participant was given a short training session. The experiment tasks were explained to them, and they were instructed to follow the sphere as closely as possible. They were then given the opportunity to practice both tasks for about 40 seconds in order to familiarize themselves (example words were used). Participants that were not following the sphere closely enough were corrected by the experimenter so that all participants maintained a close distance. After completing the training, the participants completed the four experiment trials, each lasting 115 seconds. After trials with a divided task, participants removed the

display and completed a word recognition test on a desktop computer. After trials

with only a single task, the participants were given the option of removing the display

and taking a brief break, if desired. The experimental session was concluded after

completing all four trials.

5.6.3   Post-Experiment

Immediately after completing the experimental session, the participants filled out

the post-test for simulator sickness. Afterwards, they were debriefed and the partici-

pants were given a final opportunity to ask questions or provide comments.

5.7   Results

Unless otherwise noted, all statistical results reported in this section use a signifi-

cance value of $\alpha = .05$. All analyses used Type III sum of squares to correct for the

uneven gender proportions within each group.

5.7.1   Target Distance

The average target distance measurements were treated with a 4x2x2x2 mixed

analysis of variance (ANOVA), testing the between-subjects effects of travel technique

and gender and the within-subjects effects of task type (single task or divided task)

and task difficulty (simple or complex). The analysis revealed a significant main

effect for travel technique, $F(3,124) = 5.06$, $p < .01$, $\eta_p^2 = .11$. None of the other

main effects or interaction effects were significant. Post-hoc analysis with the Tukey

HSD test showed that the real walking technique allowed participants to maintain a

closer average distance to the target than the pointing technique over all trials, $p <$

.01. However, none of the other comparisons were significant. Figure 5.3 shows the

Target Distance Results
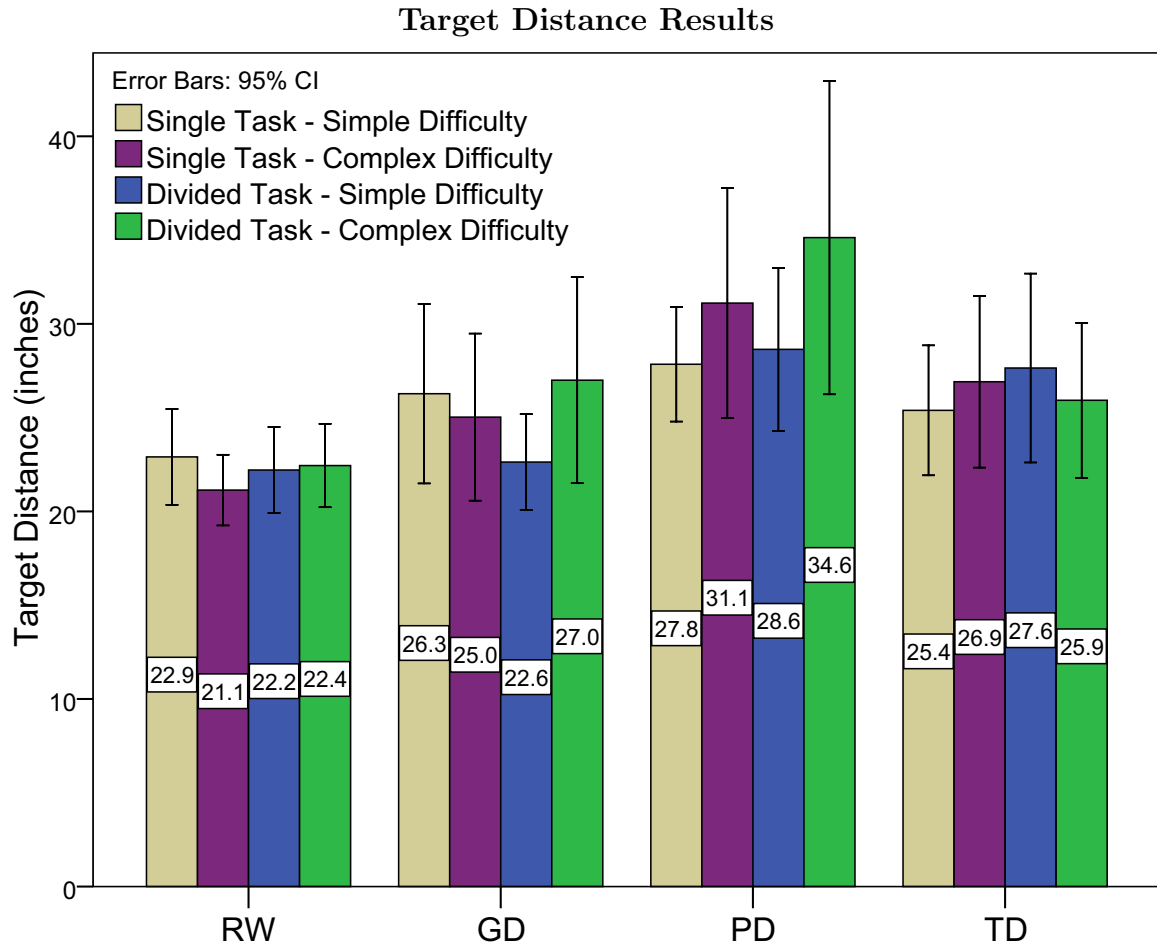
Figure 5.3: Mean target distance results (in inches) across travel conditions for all four trials with varying task type (single or divided) and task difficulty (simple or complex). Overall, the real walking (RW) technique performed significantly better than the pointing-directed (PD) technique. No other comparisons were significantly different.

mean results for target distance by task type and difficulty.

To evaluate learning effects, the target distance data was analyzed based on trial order. A 4x2x4 mixed analysis of variance was performed, testing the between-subjects effects of travel technique and gender and the within-subjects effect of trial number (1-4). Mauchly's test indicated that the assumption of sphericity was violated (χ^2 = 83.40, p < .01), so degrees of freedom were corrected using a Greenhouse-Geisser estimation (ϵ = .67). The analysis revealed a significant interaction effect between

Learning Effects
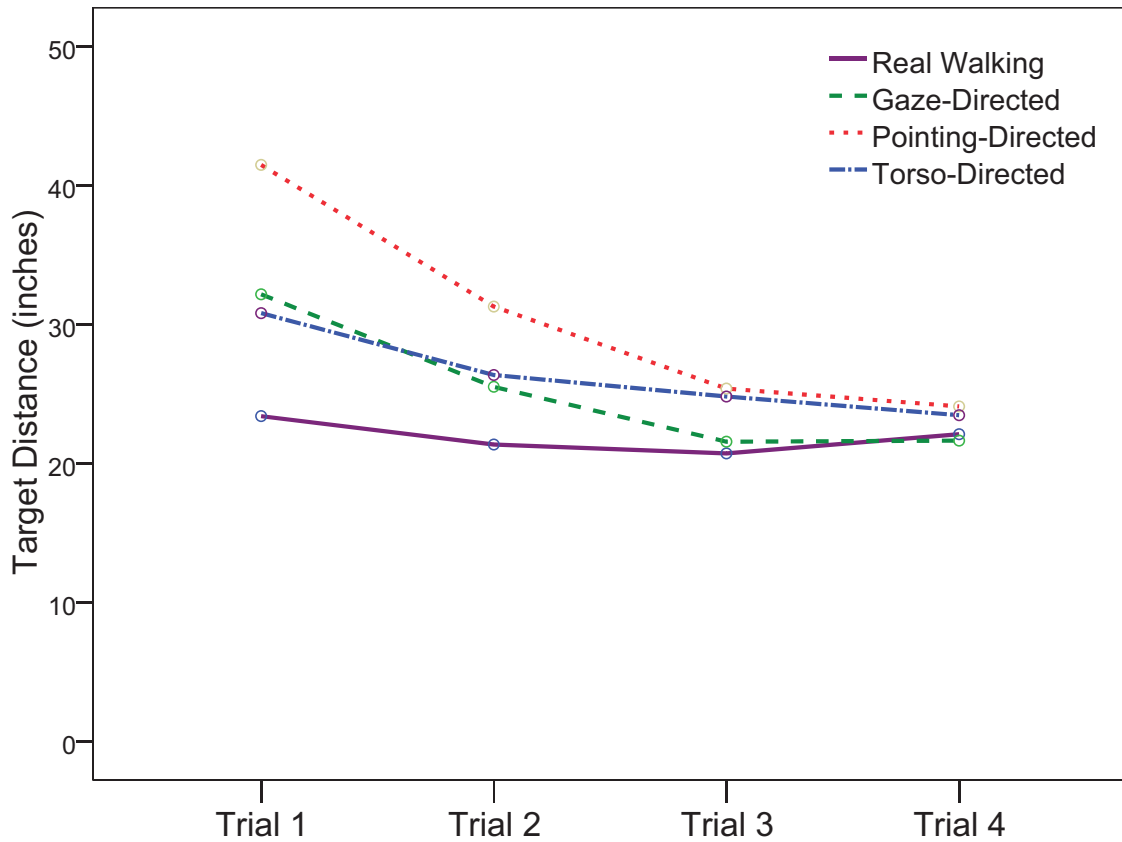
Figure 5.4: Mean target distance results (in inches) for each travel technique accord-ing to trial order. In general, participants in the virtual travel techniques steadily improved throughout the experiment, approaching the performance of the real walk-ing participants.

trial number and travel technique, $F(6.06,242.54) = 3.138$, $p < .01$, $\eta_p^2 = .07$, and a significant main effect for trial number, $F(2.02,242.54) = 25.12$, $p < .01$, $\eta_p^2 = .17$. The other interaction effects were not significant. Figure 5.4 shows a graph of the target distance results for each travel technique across the four trials.

We conducted post-hoc analysis using paired-samples t-tests to compare distances between the first and last trials using a Bonferroni corrected significance value of α = .0125 to reduce error in multiple comparisons. In the RW condition, there was not a significant learning effect from the first trial ($M = 23.76$, $SD = 6.49$) to the last

trial ($M = 22.05$, $SD = 6.65$), $p = .07$. In the GD condition, participants improved from the first ($M = 32.13$, $SD = 14.23$) to last trial ($M = 21.41$, $SD = 8.70$), $p < .01$. Participants in the TD condition also improved from the first ($M = 31.83$, $SD = 13.39$) to the last trial ($M = 23.26$, $SD = 8.56$), $p < .01$. The largest difference, however, was in the PD condition, where participants strongly improved from the first ($M = 41.16$, $SD = 21.60$) to the last trial ($M = 24.49$, $SD = 7.83$), $p < .01$. These results indicate that participants may benefit from practice using virtual travel techniques; however, training is not necessary when using real walking.

5.7.2   Response Scores

For response scores, we excluded one participant from the analysis who did not perform the secondary task during the session. The average response scores were then treated with a 4x2x2 ANOVA, testing the between-subjects effects of travel technique and gender and the within-subjects effect of task difficulty. The analysis revealed a significant interaction effect between difficulty and gender, $F(1,119) = 3.87$, $p = .05$, $\eta_p^2 = .03$, and significant main effect for task difficulty, $F(1,119) = 4.50$, $p = .04$, $\eta_p^2 = .04$. The main effect for gender was not significant, $p = .72$, nor were any of the other effects. We conducted post-hoc analysis of the gender-difficulty interaction using paired-sample t-tests with a Bonferroni corrected significance value of $\alpha = .025$ to reduce error in multiple comparisons. Males performed worse for complex difficulty ($M = .86$, $SD = .19$) than simple difficulty ($M = .93$, $SD = .11$), $p = .02$. However, the response scores for females were not significantly different between complex difficulty ($M = .88$, $SD = .16$) and simple difficulty ($M = .89$, SD

Response Score Results
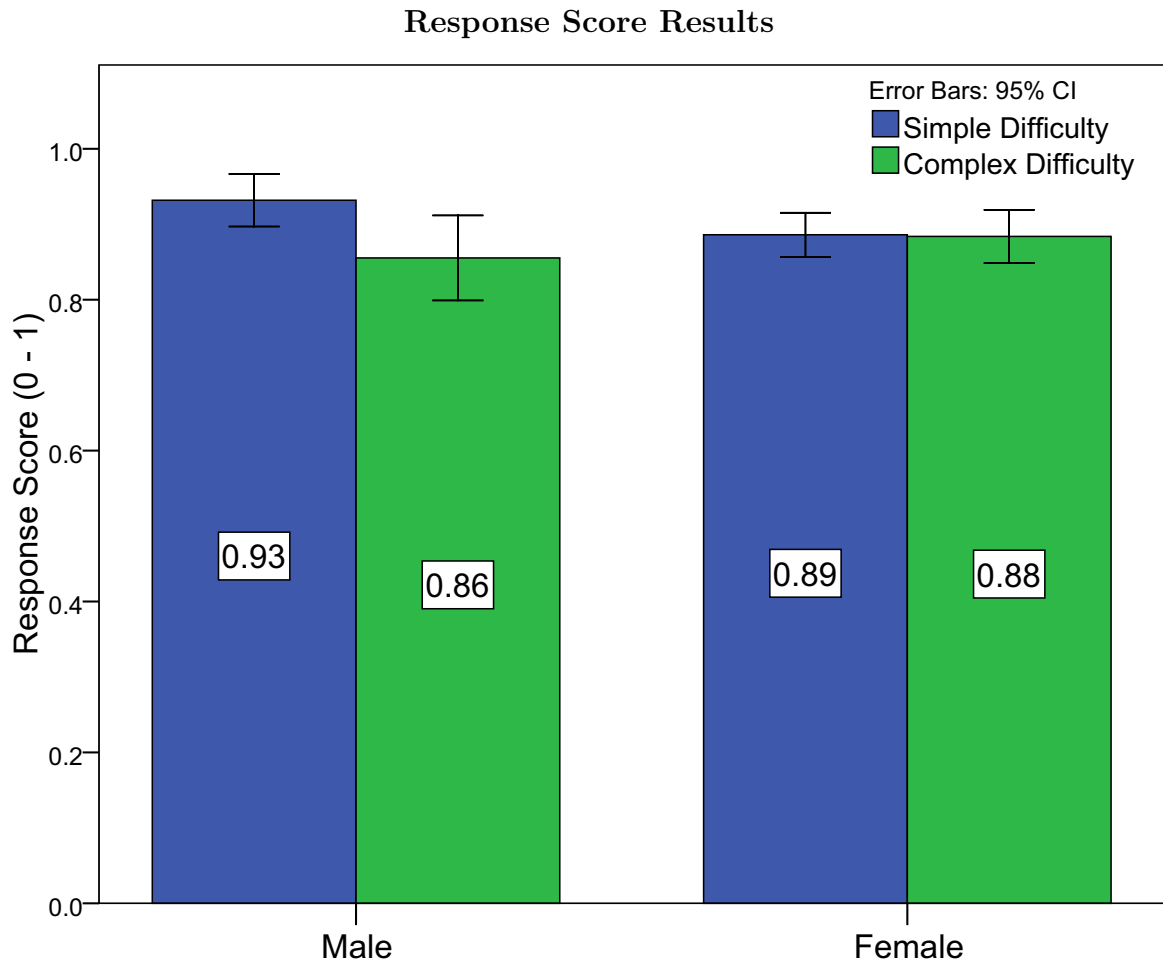
Figure 5.5: Response scores (between 0 and 1) were calculated by subtracting the percentage of false alarms (responding to distractors) from the percentage of hits (responding to category words). Higher scores corresponding to better performance. Males performed worse in the complex difficulty than the simple difficulty, but this difference was not observed for females.

$= .13$), $p = .92$. Figure 5.5 shows the mean response score results by gender.

5.7.3 Response Times

In our analysis of response times, we trimmed 4 extreme outliers (2 from GD, 2 from PD) which were greater than 3 standard deviations from the mean to avoid skewing the results. The average reaction times were treated with a 4x2x2 ANOVA, testing the between-subjects effects of travel technique and gender and the within-subjects

Response Time Results
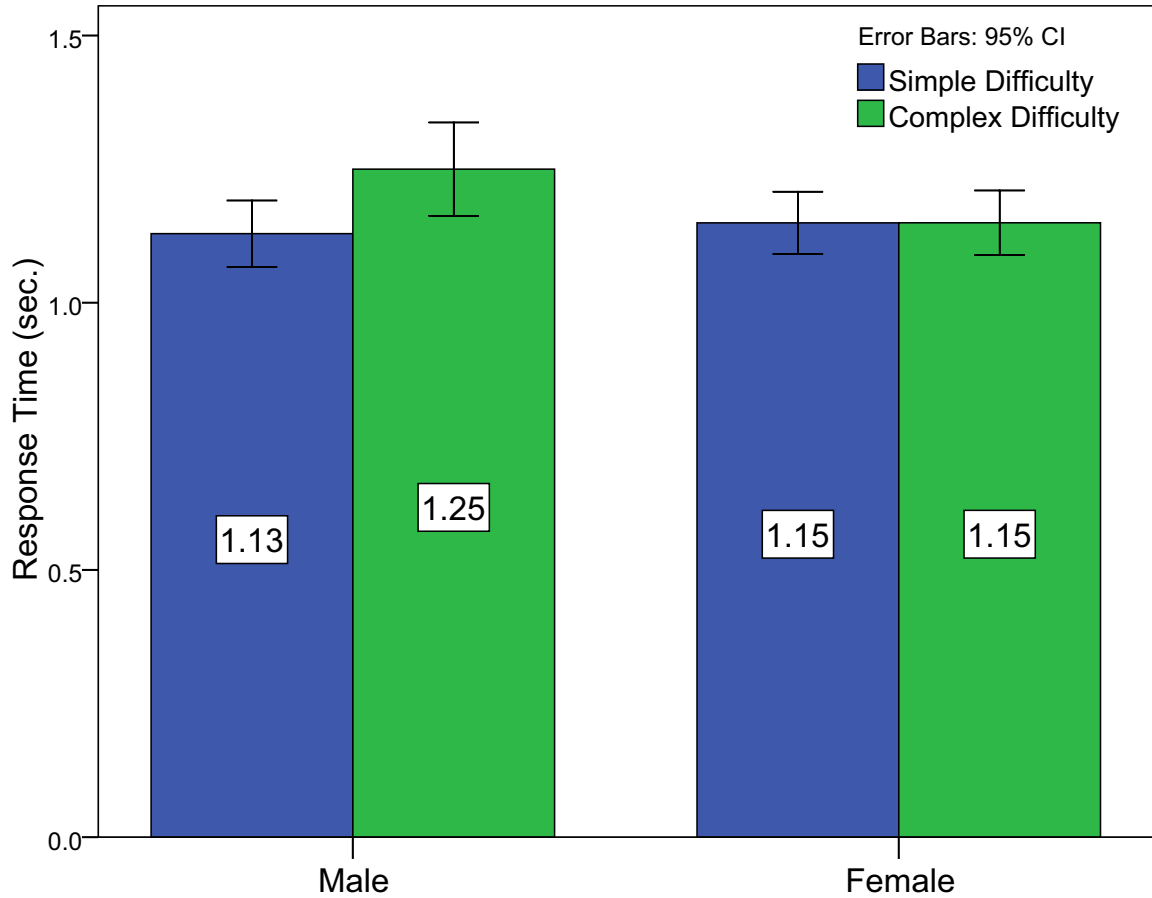
Figure 5.6: Mean response times (in seconds) according to gender and task difficulty (simple or complex). Lower times correspond to better performance. Males responded slower in the complex difficulty than the simple difficulty, but this difference was not observed for females.

effect of task difficulty. The analysis revealed a significant interaction effect between difficulty and gender, $F(1,116) = 4.77$, $p = .03$, $\eta_p^2 = .04$, and a significant main effect for difficulty, $F(1,116) = 4.62$, $p = .03$, $\eta_p^2 = .04$. The main effect for gender was not significant, $p = .35$, nor were any of the other effects. We conducted post-hoc analysis of the gender-difficulty interaction using paired-sample t-tests with a Bonferroni corrected significance value of $\alpha = .025$. Males reacted slower for complex difficulty ($M = 1.25$ sec., $SD = 0.29$) than simple task difficulty ($M = 1.13$ sec.,

Word Recognition Results
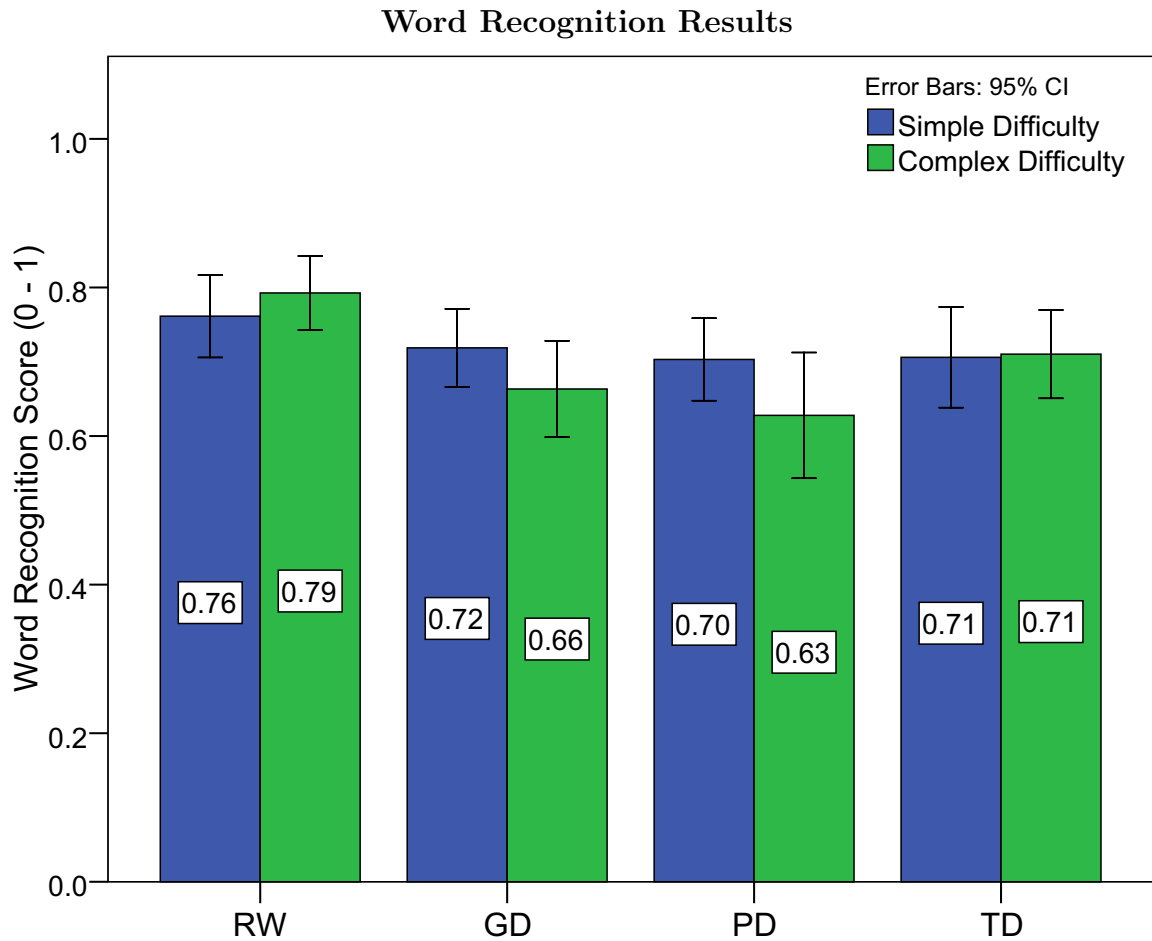
Figure 5.7: Mean word recognition test scores (between 0 and 1) according to travel technique and difficulty (simple or complex). Higher numbers correspond to better performance. Overall, the real walking (RW) technique performed significantly better than the pointing-directed (PD) technique. No other comparisons were significant.

$SD = 0.20$), $t(43) = 2.85$, $p < .01$. However, the reaction times for females were not significantly different between complex difficulty ($M = 1.15$ sec., $SD = 0.27$) and simple difficulty ($M = 1.15$ sec., $SD = 0.26$), $p = .99$. Figure 5.6 shows the mean response time results by gender.

5.7.4   Word Recognition Test

Word recognition scores and confidence scores were each treated with a 4x2x2 mixed ANOVA, testing the between-subjects effects of travel technique and gender

Table 5.1: Mean (SD) results for word recognition scores and confidence ratings. The word recognition scores (between 0 and 1) were calculated by subtracting the percentage of false alarms from the percentage of hits. Confidence ratings are measured on a 6-point scale (1 = very confident no, 2 = somewhat confident no, 3 = not very confident no, 4 = not very confident yes, 5 = somewhat confident yes, 6 = very confident yes).

	Condition	Recognition	Confidence
RW	Simple Difficulty	.76 (.15)	5.51 (.48)
	Complex Difficulty	.79 (.14)	5.52 (.43)
GD	Simple Difficulty	.72 (.15)	5.37 (.38)
	Complex Difficulty	.66 (.18)	5.30 (.44)
PD	Simple Difficulty	.70 (.15)	5.43 (.47)
	Complex Difficulty	.63 (.23)	5.23 (.60)
TD	Simple Difficulty	.71 (.19)	5.36 (.51)
	Complex Difficulty	.71 (.16)	5.38 (.43)

and the within-subjects effect of task difficulty. For recognition scores, the main effect for travel technique was significant, $F(3,120) = 3.29$, $p = .02$, $\eta_p^2 = .08$. None of the other effects were statistically significant. Post-hoc analysis with the Tukey HSD test revealed that scores for real walking were higher than pointing-directed, $p = .01$. The analysis for confidence scores was not significant. Figure 5.7 shows the mean word recognition scores for each task difficulty across the travel conditions. Table 5.1 shows the mean and standard deviation results for the recognition scores and confidence ratings.

5.7.5 Simulator Sickness Questionnaire

For the simulator sickness analysis, we identified an extreme outlier that received a very high score on the pre-test (greater than 75). This indicates that the participant was already feeling ill prior to the experiment, so we excluded this participant from the SSQ analysis to avoid skewing the results. A 4x2x2 mixed ANOVA was performed on simulator sickness scores, testing the between-subjects effect of travel technique and gender and the within-subjects effect of time (before and after the experimental session). We found a significant main effect for time, $F(1,119) = 10.50$, $p < .01$, $\eta_p^2 = .08$, indicating that simulator sickness increased from before the experimental session ($M = 9.72$, $SD = 11.68$) to afterwards ($M = 14.46$, $SD = 15.04$). None of the other effects were significant.

5.7.6 Spatial Ability Pre-Tests

The scores from Vandenberg & Kuse (VK), Guilford-Zimmerman (GZ), and VR spatial ability tests were each treated with a univariate ANOVA testing the pre-test scores across the travel conditions. The GZ test was not significant, $p = .57$, nor was the VR test, $p = .31$. The VK test was also not significant, $p = .07$.

5.7.7 Video Game Experience

The two video game experience measures (self-ratings of 3D game experience and hours spent playing video games in an average week) were each treated with a uni-variate ANOVA testing the distribution of video game experience across the between-subjects travel conditions. The results for 3D game experience ratings were not sig-

nificant, $p = .60$. The analysis for hours spent playing video games was also not significant, $p = .47$. Additionally, Pearson correlation coefficients were calculated to assess the relationship between the two video game experience ratings and the virtual environment task performance measurements. However, none of the correlations were significant.

5.8   Discussion

Participants that used the real walking technique were able to perform the primary navigation task better than those using the pointing-directed technique, as indicated by our target distance measure. These results are consistent with the findings of Experiment 1, which showed that the pointing-directed technique tends to underperform real walking on measures of navigation task performance. We also noticed learning effects for virtual travel techniques throughout the experiment, and by the fourth trial, performance on the navigation task was almost as good as real walking. These results suggest that user performance will improve with training and practice with virtual travel techniques; however, training does not appear to be necessary when using real walking.

We also found that participants using real walking performed better on a word recognition test than those using pointing-directed travel. This is an interesting result, especially since Experiment 1 was not able to find such an effect. We suggest that Experiment 3 had a more sensitive experimental design since it avoided potential biases from individual differences in wayfinding strategy or navigation proficiency. In summary, our word recognition results indicate that participants in the real walking

condition may have had more spare cognitive capacity to process and encode stimuli than participants in the pointing-directed condition. This is likely due to the fact that in the pointing-directed condition, the controlling hand was charged with an extra task and participants needed to visually track and correct their travel direction.

Considering that torso-directed travel is rarely used in practice, it is interesting to note that the results for this technique were similar to gaze-directed travel. It might be possible that the torso-directed technique could be used to decouple the view and travel direction without introducing the drawbacks of the pointing-directed technique, although the additional body tracking requirement may add additional encumbrance. Ultimately, more evaluation is necessary to compare the two techniques before conclusions can be drawn.

Though females and males were evenly distributed across the travel conditions, there was an uneven gender proportion overall with roughly two females per male. The fact that fewer males were willing to volunteer may have resulted in lower statistical power to detect effects in the male population relative to females. Despite this, we still found that males received lower response scores and took longer to respond in the complex difficulty trials than simple difficulty trials; however, neither of these effects were observed for females. It should be noted that while these gender differences may be pertinent when designing virtual environments that require multitasking, but the impact may be limited only to similar tasks performed under the same conditions. Thus, the nature and goal of the virtual environment tasks must be carefully considered to determine whether similar effects on performance can be expected under different conditions.

The results of many studies have indicated that gender differences in spatial abilities tend to favor males [75]. Conversely, it is also generally accepted that females tend to have superior verbal ability compared to males [31]. However, the gender difference we observed occurred in a multitasking situation. Male performance suffered on the verbal attention task as the simultaneous spatial task became more difficult, whereas female performance was not similarly impeded. While there have been several studies of cognitive abilities during performance of concurrent tasks (e.g. [57]), we were not able to locate any references in the literature that reported gender differences in a divided attention spatial/verbal task similar to this scenario. However, in a recent study of multitasking, gender discrepancies were found on a different type of cognitive test, with similar results favoring females over males [53]. Ultimately, further investigation is required to understand the nature of the gender effects we observed during this experiment.

An increase in simulator sickness after the experimental session was expected, since the participants were immersed for the virtual reality spatial test, training session, and four experimental trials. Overall, the increase in reported simulator sickness was very slight. Additionally, a recent study found that the simulator sickness pre-test may bias participants towards reporting higher simulator sickness on the post-test [81], which is another possible explanation for this small increase.

CHAPTER 6: DESIGN GUIDELINES

Based on our experiments to evaluate travel techniques in immersive virtual environments, we recommend the following guidelines for designing virtual reality applications using head-mounted displays. Since the choice of appropriate travel technique depends upon the goal of the application, it is up to the developers of a virtual reality application to determine which goals are most pertinent. Thus, these guidelines can assist developers in weighing the potential benefits of a travel technique against any tradeoffs or practical limitations. Table 6.1 summarizes these guidelines.

6.1 Minimizing Cognitive Difficulty

The results of Experiment 3 suggest that participants using real walking had more spare cognitive capacity to process and encode stimuli than those using pointing-directed travel. As a result, we recommend that real walking be used over pointing-directed travel for applications which require a high degree of user attention or minimal levels of distraction. Given our results, it seems likely that gaze-directed and torso-directed travel fall somewhere between those two extremes. Since the differences, if present, were too small to distinguish from either real walking or pointing-directed travel, some developers may choose to use them as cheaper alternatives to real walking. Maintaining user attention is important for applications which require high levels of immersion to be effective, such as virtual reality exposure therapy for

Table 6.1: Summary of Design Guidelines. Relative rankings of [1]real walking, [2]gaze-directed, [3]torso-directed, and [4]pointing-directed travel according to the goal of the application.

Goal of Application	RW[1]	GD[2]	TD[3]	PD[4]
Minimizing Cognitive Difficulty	1	2*	2*	3
Supporting Information Gathering	1	1	1	1
Supporting Efficient Navigation	1	2	2*	3
Maximizing Similarity to Real World	1	2	2	2
Reducing Simulator Sickness	2	1	1	1
Supporting Untrained Users	1	2	2	3

* could not be statistically verified

the treatment of psychological disorders.

6.2   Supporting Information Gathering

Experiments 1 and 2 used tests of memory about information gathered during exploration of the environment, and none of the travel techniques appeared to be better for supporting this type of behavior. In particular, the results of Experiment 2 indicated that real world participants were able to gather and recall more information about the environment, and even though the participants in the virtual environment conditions performed worse, travel technique did not appear to play a role in this difference. As such, we suggest that for applications in which the goal is to gather as much information as possible from the environment, any of the four travel techniques may be used. However, we also note that there appears to be significant room for improvement in supporting this behavior in virtual environments as compared to the

real world in reasons unrelated to travel technique. This guideline may be useful for domains where learning about the virtual environment is an important goal, such as education or architecture.

6.3   Supporting Efficient Navigation

The results of Experiment 1 showed that real walking allowed participants to complete the maze faster and with fewer collisions with the virtual geometry than gaze-directed and pointing-directed travel. Furthermore, in Experiment 3, real walkers were able to perform the navigation task better than those using the pointing-directed technique. Thus, for applications where users need to navigate through an environment quickly and efficiently, real walking may provide the best performance. However, this is likely due to the fact that it is easier to avoid collisions when walking, so this guideline may not apply to large, open environments where there are few obstacles to avoid. These results are widely applicable, since efficient navigation is a general goal for virtual environments across many application domains.

6.4   Maximizing Similarity to Real World

In Experiment 2, analysis of measures calculated from tracker data revealed that real walkers exhibited movement behavior that was more similar to real world motion than gaze-directed travel. Additionally, the path visualizations from Experiment 1 showed strong qualitative differences between walking and virtual travel. In general, real walking provides an experience that is more similar to the real world than virtual travel. This may be pertinent for applications which need to be realistic as possible to facilitate knowledge transfer to real world scenarios, such as military training systems.

6.5   Reducing Simulator Sickness

Real walkers reported significantly higher degrees of simulator sickness than those using gaze-directed travel in Experiment 2. Though we did not observe this effect in the other experiments, simulator sickness is known to increase with exposure time, and Experiment 2 had the longest continuous exposure to the virtual environment (approximately six minutes). We conclude that the increased physical motion when using real walking may contribute to participants' symptoms of simulator sickness more than virtual travel. It is interesting to note that Experiment 3 had the longest total exposure time (approximately ten minutes), but participants were given multiple opportunities to take breaks. As a result, we recommend that virtual environment applications using real walking for long periods of immersion should allow users to take breaks, if possible.

6.6   Supporting Untrained Users

The learning effects in Experiment 3 suggested that user performance using virtual travel techniques will improve with training and practice. This is especially important for pointing-directed travel, since it consistently performed the worst throughout the experiments. However, by the end of the experiment, virtual travel performance on a spatial pursuit task nearly approached that of real walking participants. Therefore, for tasks that require accurate and efficient travel, we recommend that untrained users be given ample opportunity to practice moving through the environment. Based on the results from this experiment, it appears that 8 minutes of active practice may be sufficient for the average user to gain proficiency in using virtual travel techniques.

CHAPTER 7: CONCLUSION

7.1   Summary

This dissertation described a series of three user studies to experimentally evaluate the benefits and drawbacks of real walking relative to common virtual travel techniques for immersive virtual environments. The contributions of this body of work are as follows. In Experiment 1, we created a virtual environments that was larger and more complex than previous studies of real walking, which allowed us to measure the effect of travel technique on information gathering, task completion time, and collision avoidance. In Experiment 2, we compared exploration of a complex virtual maze to an identical real world environment, which had not been previously studied in the context of comparing the cognitive effects of travel techniques. Finally, in Experiment 3, we improved on previous measures of the cognitive difficulty of travel using a novel divided attention task.

In general, the results of these studies have revealed several advantages for real walking over virtual travel techniques. However, real walking does not provide benefits in all situations, and these experiments have also identified conditions when virtual travel techniques may be used as less expensive alternatives. Thus, we provided guidelines to outline the advantages and disadvantages of these techniques with respect to the particular goals of the virtual environment application. Developers of

future virtual reality applications may use these guidelines to weigh the benefits of using a certain travel technique against potential drawbacks or practical limitations.

7.2   Relationship with Previous Literature

Our results showed that real walking is cognitively easier than pointing-directed travel. Previous work in this area has focused on using information gathering metrics [11] [36] [82], and so the results of these studies were either not significant or required future investigation to probe possible confounds. The choice of evaluated travel technique has also been inconsistent across these studies. Experiment 3 provided a comprehensive evaluation using a more sensitive divided attention task, addressing many of the open questions from previous work. Additionally, our information gathering results from Experiments 1 and 2 are consistent with these previous studies.

Our results across studies have shown that real walking is more efficient than virtual travel and results in better performance on navigation tasks. These results are largely consistent with previous findings that have noted advantages for real walking in search task performance [54] [55] and spatial orientation [16]. Additionally, our results showed that real walking results in behavior that is more similar to real world motions, which echo previous findings [78].

In Experiment 2, we found that real walking seemed to increase reported levels of simulator sickness, which contradicts the results of a previous study that reported a decrease in motion sickness when using real walking [16]. However, the motion sickness rating used by the previous study was based on a single self-report, which is less detailed than the extensively validated simulator sickness questionnaire used

in our experiments. Furthermore, differences in the hardware and experiment setup between the studies makes it difficult to compare the two results. However, other previous work investigated simulator sickness in the context of travel technique and did not find significant differences [82], which is consistent with the results of Experiments 1 and 3.

7.3   Future Work

While this research has provided much insight into the impact of design decisions for travel in immersive virtual environments, several questions remain open for future investigation. First, given the possibility that the torso-directed technique may provide the primary advantage of the pointing-directed technique without the cognitive drawbacks, it would be valuable to compare these techniques on tasks where the user can benefit from decoupling the travel and view direction. In general, little data exists on how often users actually travel in different directions than they are looking, and we were unable to analyze this behavior since the hand/torso tracker data was not recorded during our experiments. Additionally, while our experiments have revealed an interesting gender effect on a divided attention task, the explanation for this phenomenon remains unclear. Future work is necessary to reveal the nature of these gender effects and their implications for the design of virtual environment applications.

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APPENDIX A: MATERIALS FROM EXPERIMENT 1

This appendix contains materials used in Experiment 1, which was reported in Chapter 3. The following materials are included, listed in order of appearance:

1. The participant information sheet

2. The informed consent form

3. The object recall test

4. The object recognition test

5. The sketch map test

6. The object placement test

7. The debriefing statement given to participants after the experiment

Effects of Virtual Travel Technique on Cognitive Tasks
Participant Information

Part I: Pre-Experiment
1. We will check if you meet all the qualifications to be a participant in this study.
2. We will explain the entire experiment to you and answer any questions that you have.
3. You will review a consent form that describes aspects of the study. If you agree, please sign the form.
4. You will be asked to complete a set of questionnaires on spatial orientation and simulator sickness.

Part II: The Experiment Session
1. We will show you the equipment we will use: the head-mounted display (HMD) and a hand-held joystick. We will answer any questions you have about them.
2. We'll help you adjust the HMD so that you can see the images properly and in stereo. You can ask to discontinue the experiment at any time.
3. Next, you will practice navigation in a training virtual environment.
4. When you are ready, your virtual environment will change to the experiment virtual environment.
5. Your task is to explore the environment until you reach the end of the maze.

Part III: Post-Experiment
1. Immediately after exiting the virtual environment, you will be asked to fill out a questionnaire on simulator sickness.
2. Next, you'll be asked to list as many objects as you can remember from the environment.
3. In the next step, you'll be given a list of objects, and you will be asked to identify whether or not each object was present in the environment.
4. You will be provided with blank sheets of paper and asked to sketch a map of the floor plan you just explored.
5. You will be given a map and list of items from the environment, and asked to label their locations on the map where you remember seeing them
6. The investigator will ask you if you have any other comments about the experience or questions that you'd like to ask.

Please answer the questions thoughtfully; your answers are a key element in making our study produce meaningful and useful results.

Department of Computer Sc
College of Computing and Inform
9201 University City
Charlotte, NC 2

Informed Consent

Project Title and Purpose:
You are invited to participate in a research study entitled "Effects of Virtual Travel Technique on Cognitive Tasks." The purpose of this experiment is to investigate the effects of different modes of travel in virtual reality environments. We will study different modes of locomotion to determine which are better suited for various tasks in VR environments.

Investigator(s):
> Larry F. Hodges, Ph.D. and Evan A. Suma, B.A.
> Office: Woodward 403F
> Email: lfhodges@uncc.edu
> Phone: 704-687-6128
> Please contact Evan Suma with questions regarding this research.

Description of Participation:
You will be randomly assigned to one of the different travel conditions and asked to navigate through a virtual environment. Information about your exploration through the environment will be logged by the computer. You will be asked to fill out questionnaires prior to and immediately following the session. The session will last about one hour. Approximately 30 people will take part in this study. The data collected during this experiment will be compared to existing data from a previous experiment which followed an identical procedure.

Length of Participation:
Your participation in this project will require one laboratory session lasting approximately one hour.

Risks and Benefits of Participation:
While using virtual environment systems, some people experience slight symptoms of disorientation, nausea, or dizziness. These can be similar to "motion sickness" or the feeling experienced in wide-screen movies and theme park rides. We do not expect these to be strong or to last after participants leave the laboratory. You will often be reminded that if you feel uncomfortable and wish to stop the experiment, you are free to do so at any time without penalty.

During this study, you will benefit from exposure to virtual reality technology that is typically inaccessible to the general public.

Volunteer Statement:
You are a volunteer. The decision to participate in this study is completely up to you. If you decide to be in the study, you may stop at any time. You will not be treated any differently if you decide not to participate or if you stop once you have started.

Confidentiality versus Anonymity:
The data collected by the Investigator will not contain any identifying information or any link back to you or your participation in this study. The following steps will be taken to ensure this anonymity: The data collected will be kept anonymous and confidential by randomly assigning a participant number for each participant and only referring to the data by the given participant number. In addition, names of the participants will not be collected. Any data that is documented on paper will be stored and locked in a cabinet for one year only with access only given to the primary and co-investigators listed on this form.

Fair Treatment and Respect:
UNC Charlotte wants to make sure that you are treated in a fair and respectful manner. Contact the University's Research Compliance Office (704.687.3309) if you have any questions about how you are treated as a study participant. If you have any questions about the project, please contact Larry F. Hodges.

Participant Consent
I have read the information in this consent form. I have had the chance to ask questions about this study, and those questions have been answered to my satisfaction. I am at least 18 years of age or am an emancipated minor*, and I agree to participate in this research project. I understand that I will receive a copy of this form after it has been signed by me and the Principal Investigator.

_____ _____ _____
Participant Name (PLEASE PRINT) Participant Signature   DATE

_____ _____
Investigator Signature   DATE

*Emancipated Minor (as defined by NC General Statute 7B-101.14) is a person who has not yet reached their 18th birthday and meets at least one of the following criteria: 1) has legally terminated custodial rights of his/her parents and been declared 'emancipated' by a court; 2) is married, or 3) is serving in the armed forces of the United States.

Object Recall

Directions:

Please attempt to list as many objects as you can remember from the environment on the blank sheet provided.

Time: 5 minutes

_____   _____

_____   _____

_____   _____

_____   _____

_____   _____

_____   _____

_____   _____

_____   _____

_____   _____

Object Recognition

Directions:
For this task, you will be given a list of objects. Some of the objects were present in the environment and some were not. If you remember the object from the environment, write 'Y' next to the object. If you think the object was not in the environment, write 'N'.

Time: 8 minutes

1. ____ Clock

2. ____ Bowling Ball

3. ____ Book

4. ____ Candy Cane

5. ____ CD

6. ____ Phone

7. ____ Painting

8. ____ Rug

9. ____ Shield

10. ____ Glass Bottle

11. ____ Teapot

12. ____ Stapler

13. ____ Stool

14. ____ Chalkboard

15. ____ Potted Plant

16. ____ Balloon

17. ____ Candle

18. ____ Milk Carton

19. ____ Rose

20. ____ Shoe

21. ____ Banana

22. ____ Trash Can

23. ____ Soda Can

24. ____ First Aid Kit

25. ____ Guitar

26. ____ Key

27. ____ Ceiling Fan

28. ____ Metal Grate

29. ____ Chair

30. ____ Television

31. ____ Airplane

32. ____ Sword

33. ____ Bird

34. ____ Apple

35. ____ Sailboat

36. ____ Helicopter

Sketch Sheets

Directions:

For this task, you will be given two blank sketch sheets. For each floor, please sketch a map of the floor plan you just explored.

Time: 5 minutes

Map Labeling

Directions:

For this task, you will be given:

- a list of objects in the environment
- a map of each floor you explored

For as many objects as you can, please indicate the location of the object in the environment by writing the item number on the map in the location you remember.

Time: 10 minutes

Items

1. Chair
2. First Aid Kit
3. Balloon
4. Potted Plant
5. Glass Bottle
6. Ceiling Fan
7. Rug
8. Key
9. Shield
10. Trash Can
11. Candy Cane
12. Bird
13. Stool
14. Apple
15. Airplane
16. Soda Can
17. Sailboat
18. Clock
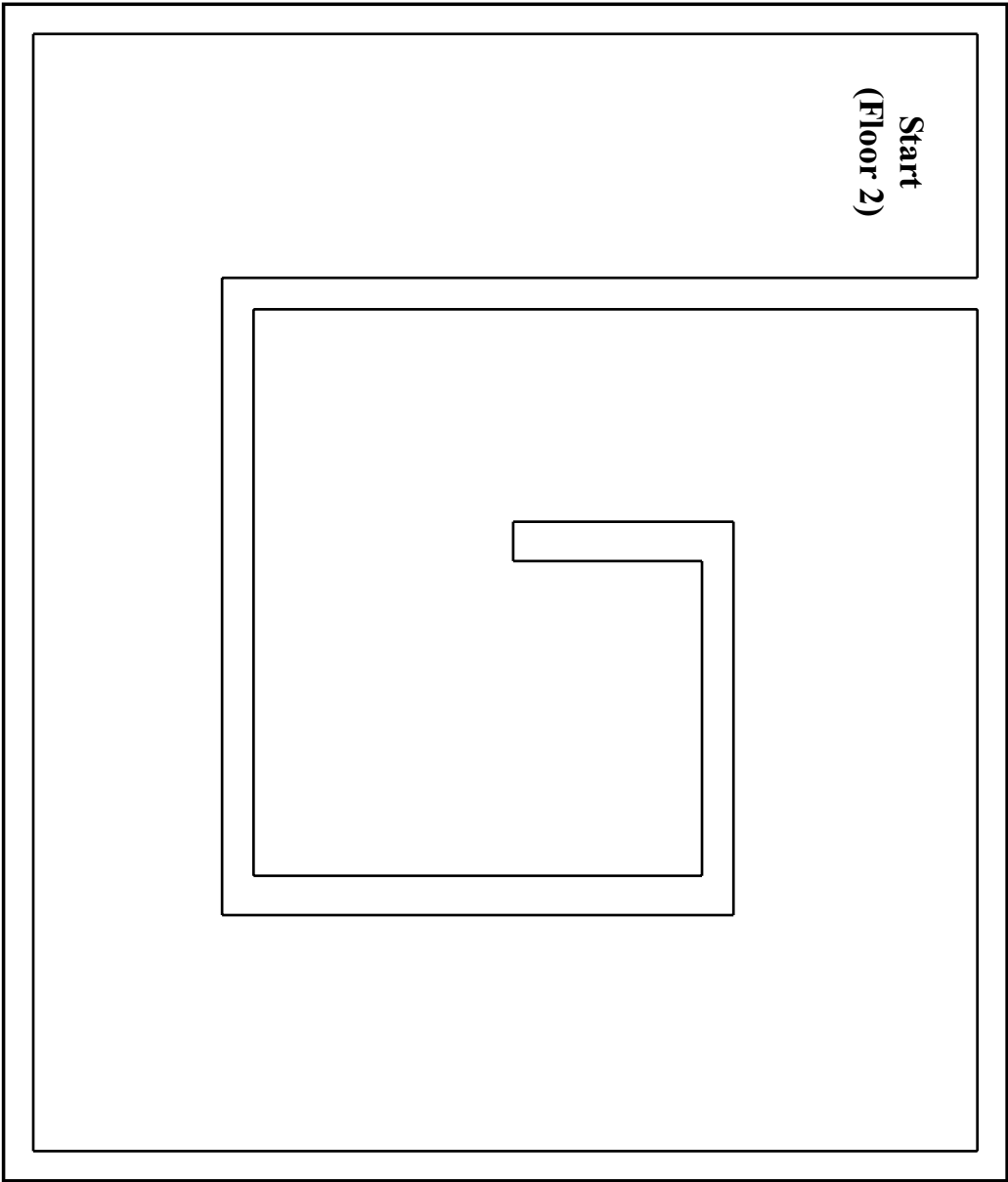
First Floor Map

ELEVATOR UP

START (Floor 1)

Second Floor Map

**Start
(Floor 2)**

Debriefing

Numerous techniques have been implemented in Virtual Environments (VEs) to allow a participant to move about a virtual space. In general, they can be categorized as either techniques that try to replicate the energy and motions of walking or as purely virtual travel techniques. Examples of the former include treadmills and walking-in-place schemes. Examples of the latter usually utilize a joystick to "fly" through a space in a direction specified by either head orientation or a handheld pointer. All these approaches assume that the physical tracked space available to the user is smaller than the virtual space that is to be experienced.

The purpose of this experiment is to investigate the differences on cognition and understanding of a virtual environment when explored using common joystick-based travel techniques versus walking about the space in a natural manner. To assess these differences, we are performing an experiment between conditions. In one condition, the participants are allowed to walk about the space in a natural manner. In the second condition, the participants navigate via a joystick trigger that moves them in the direction they are looking. In the third condition, the participants navigate via a joystick trigger that moves them in the direction that their hand is pointing. We hypothesize that participants that explore the environment using a real walking technique will experience a greater awareness and understanding of the environment than those who use a virtual travel technique.

I would like to ask you not to inform anyone else about the purpose of this study. Thank you for participating. If you have questions about the final results, please contact Evan A. Suma (687-8582, easuma@uncc.edu) or Dr. Larry F. Hodges (687-8559, lfhodges@uncc.edu).

APPENDIX B: MATERIALS FROM EXPERIMENT 2

This appendix contains materials used in Experiment 2, which was reported in Chapter 4. The following materials are included, listed in order of appearance:

1. The participant information sheet for the virtual environment conditions

2. The participant information sheet for the real world condition

3. The informed consent form

4. The pre-experiment questionnaire

5. The object recall test

6. The cognition questionnaire (3 parts)

7. The object location test

8. The post-experiment questionnaire

9. The debriefing statement given to participants after the experiment

Navigation of a 3D Maze in the Virtual World
Participant Information

Part I: Pre-Experiment
1. We will check if you meet all the qualifications to be a participant in this study.
2. We will explain the entire experiment to you and answer any questions that you have.
3. You will review a consent form that describes aspects of the study. If you agree, please sign the form.
4. You will be asked to fill out a demographic survey, a pre-questionnaire on spatial orientation, and a pre-test for simulator sickness.

Part II: The Experiment Session
1. We will show you the equipment we will use: the head-mounted display (HMD) and a hand-held joystick. We will answer any questions you have about them.
2. We'll help you place the HMD over your head so that you can see the images properly and adjust it so that it fits comfortably.
3. Next, you will practice moving around in a training virtual environment.
4. When you are ready, we will load the experiment environment, and you will begin exploring a maze.
5. Your task is to explore the maze for 5 minutes. You can stop the experiment at any time with no penalty by announcing you wish to stop.
6. At the end of the allotted time, we will announce that the experiment session is over and we will help you remove the HMD.

Part III: Post-Experiment
1. Immediately after completing the experiment session, you will be asked to fill out a questionnaire on simulator sickness.
2. Next, you'll be asked to list as many objects as you can remember from the environment.
3. You will then be asked to fill out a cognition questionnaire.
4. You will be given a map and list of items from the environment, and asked to label their locations on the map where you remember seeing them.
5. You will be asked to fill out a post-experience survey.
6. Lastly, the investigator will ask you if you have any other comments about the experience or questions that you'd like to ask.

Please answer the questions thoughtfully; your answers are a key element in making our study produce meaningful and useful results.

Navigation of a 3D Maze in the Real World
Participant Information

Part I: Pre-Experiment
1. We will check if you meet all the qualifications to be a participant in this study.
2. We will explain the entire experiment to you and answer any questions that you have.
3. You will review a consent form that describes aspects of the study. If you agree, please sign the form.
4. You will be asked to fill out a demographic survey, a pre-questionnaire on spatial orientation, and a pre-test for simulator sickness.

Part II: The Experiment Session
1. We will show you the equipment we will use: a head tracker and stereo headphones. We will answer any questions you have about them.
2. We will help you place the tracker and headphones over your head and adjust them so they fit comfortably.
3. When you are ready, you will begin exploring a maze.
4. Your task is to explore the maze for 5 minutes. You can stop the experiment at any time with no penalty by announcing you wish to stop.
5. At the end of the allotted time, we will announce that the experiment session is over and we will help you remove the tracker and headphones.

Part III: Post-Experiment
1. Immediately after completing the experiment session, you will be asked to fill out a questionnaire on simulator sickness.
2. Next, you'll be asked to list as many objects as you can remember from the environment.
3. You will then be asked to fill out a cognition questionnaire.
4. You will be given a map and list of items from the environment, and asked to label their locations on the map where you remember seeing them.
5. You will be asked to fill out a post-experience survey.
6. Lastly, the investigator will ask you if you have any other comments about the experience or questions that you'd like to ask.

Please answer the questions thoughtfully; your answers are a key element in making our study produce meaningful and useful results.

UNCCHARLOTTE

Department of Computer Sc
College of Computing and Inforn
9201 University City
Charlotte, NC 2

Informed Consent

Project Title and Purpose:
You are invited to participate in a research study entitled "Navigation of a 3D Maze in the Real and Virtual World." The purpose of this experiment is to investigate the differences between navigation in the real world and navigation in a virtual environment using different travel techniques. We will study different modes of locomotion to determine which are better suited for various tasks in VR environments.

Investigator(s):
> Evan A. Suma, B.A. and Larry F. Hodges, Ph.D.
> Office: Woodward 403F
> Email: easuma@uncc.edu
> Phone: 704-687-8582
> Please contact Evan Suma with questions regarding this research.

Description of Participation:
You will be randomly assigned to one of the different travel conditions and asked to navigate through either a real or virtual maze. Information about your exploration through the environment will be logged by the computer. You will be asked to fill out questionnaires prior to and immediately following the session. The session will last about one hour. Approximately 90 people will take part in this study.

Length of Participation:
Your participation in this project will require one laboratory session lasting approximately one hour.

Risks and Benefits of Participation:
While using virtual environment systems, some people experience slight symptoms of disorientation, nausea, or dizziness. These can be similar to "motion sickness" or the feeling experienced in wide-screen movies and theme park rides. We do not expect these to be strong or last after participants leave the laboratory. You will often be reminded that if you feel uncomfortable and wish to stop the experiment, you are free to do so at any time without penalty by announcing you wish to stop.

During this study, you will benefit from exposure to virtual reality technology that is typically inaccessible to the general public.

<u>Volunteer Statement:</u>
You are a volunteer. The decision to participate in this study is completely up to you. If you decide to be in the study, you may stop at any time. You will not be treated any differently if you decide not to participate or if you stop once you have started.

<u>Confidentiality versus Anonymity:</u>
The data collected by the Investigator will not contain any identifying information or any link back to you or your participation in this study. The following steps will be taken to ensure this anonymity: The data collected will be kept anonymous and confidential by randomly assigning a participant number for each participant and only referring to the data by the given participant number. In addition, names of the participants will not be collected. Any data that is documented on paper will be stored and locked in a cabinet for one year only with access only given to the primary and co-investigators listed on this form. Any electronic data will be stored on a single computer protected by a password.

<u>Fair Treatment and Respect:</u>
UNC Charlotte wants to make sure that you are treated in a fair and respectful manner. Contact the University's Research Compliance Office (704.687.3309) if you have any questions about how you are treated as a study participant. If you have any questions about the project, please contact Evan Suma.

<u>Participant Consent</u>
I have read the information in this consent form. I have had the chance to ask questions about this study, and those questions have been answered to my satisfaction. I am at least 18 years of age or am an emancipated minor*, and I agree to participate in this research project. I understand that I will receive a copy of this form after it has been signed by me and the Principal Investigator.

_____   _____   _____

Participant Name (PLEASE PRINT)   Participant Signature   DATE

_____   _____
Investigator Signature   DATE

*Emancipated Minor (as defined by NC General Statute 7B-101.14) is a person who has not yet reached their 18th birthday and meets at least one of the following criteria: 1) has legally terminated custodial rights of his/her parents and been declared 'emancipated' by a court; 2) is married, or 3) is serving in the armed forces of the United States.

Pre-Experiment Questionnaire

Personal Information

Your age:_____   Your gender (circle one): Male / Female

Handedness (circle one): Left Handed / Right Handed

Ethnicity   (check all that apply)

_____ Hispanic or Latino

_____ American Indian or Alaska Native

_____ Asian

_____ Black or African American

_____ Native Hawaiian or Other Pacific Islander

_____ White

_____ Other (please indicate): _____

Occupational Status   (check all that apply)

_____ Undergraduate Student

_____ Masters Student

_____ Ph.D. Student

_____ University Staff

_____ Faculty

_____ Other (please indicate): _____

Directions: For each question below, please circle one option that best fits your answer to the question.

1. To what extent do you use a computer in your daily activities?

     1   2   3   4   5   6   7
(not at all)   (a great deal)

2. To what extent do you play video games on a daily basis?

     1   2   3   4   5   6   7
(not at all)   (a great deal)

3. During an average week, how many hours do you spend playing video games? (circle one)

< 1 hour   1-3 hours   3-5 hours   5-7 hours   7-9 hours   > 9hours

4. Do you consider yourself:

          A non-video game player

          A novice video game player

          An occasional video game player

          A frequent video game player

          An expert video game player

Object Recall

Directions:

Please attempt to list as many objects as you can remember from the environment.

Time: 5 minutes

_____   _____

_____   _____

_____   _____

_____   _____

_____   _____

_____   _____

_____   _____

_____   _____

Cognition Questionnaire – Part 1

Directions: Please attempt to answer these questions as best you can. If you do not remember the answer to a question, you may skip it.

1. Given what you observed in the maze, name an animal that someone who made the maze might keep as a pet.

2. Given what you observed in the maze, what flavor milkshake would you buy for the person who made this maze?

3. Given what you observed in the maze, name a place that someone who made the maze might vacation.

4. Given what you observed in the maze, what type of celebration do you think the person who made this maze prefers?

5. Given what you observed in the maze, what part of any meal is the favorite of the person who made this maze?

6. Name all the pictures you saw in the maze that were of living things.

7. Given the pictures you observed in the maze, what are some of the outdoor hobbies you might expect the person who made the maze to enjoy?

8. How many people were at the celebration? How did you arrive at your answer?

Cognition Questionnaire – Part 2

Directions: Please attempt to answer these questions as best you can. If you do not remember the answer to a question, you may skip it.

1. What animal did you hear, but not see?

2. How old is the person who owns the cake? How did you arrive at your answer?

3. What did the pictures that were taken outside have in common?

4. To use the recipe you heard, what ingredients would you need?

5. What did the pictures of animals have in common?

6. Was the party expected? How did you arrive at your answer?

7. Describe the weather in the outdoor pictures.

8. What did the foods have in common?

Cognition Questionnaire – Part 3

Directions: Please attempt to answer these questions as best you can. If you do not remember the answer to a question, you may skip it.

1. How many baby birds were in the nest?

2. What kind of tree did you see?

3. What color were the balloons?

4. What was the recipe for?

5. How many penguins did you see?

6. What color was the lifeguard's chair?

7. What color was the bow on the present?

8. What toppings were on the ice cream sundae?

Object Location Test

Directions: Write the number of the object on the provided map sheet in the location you think the object was in the maze. If the object included a sound, you can click it to hear the sound it made. If you can't remember an object's location, you can skip it.

1

click to hear sound

2

click to hear sound

3

click to hear sound

4

click to hear sound

5

6

7

8
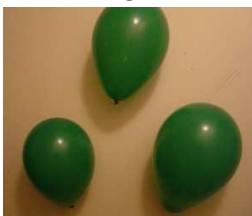
9

click to hear sound

10

click to hear sound

11

click to hear sound

12

click to hear sound

Object Locations

Entrance

Post-Experiment Questionnaire
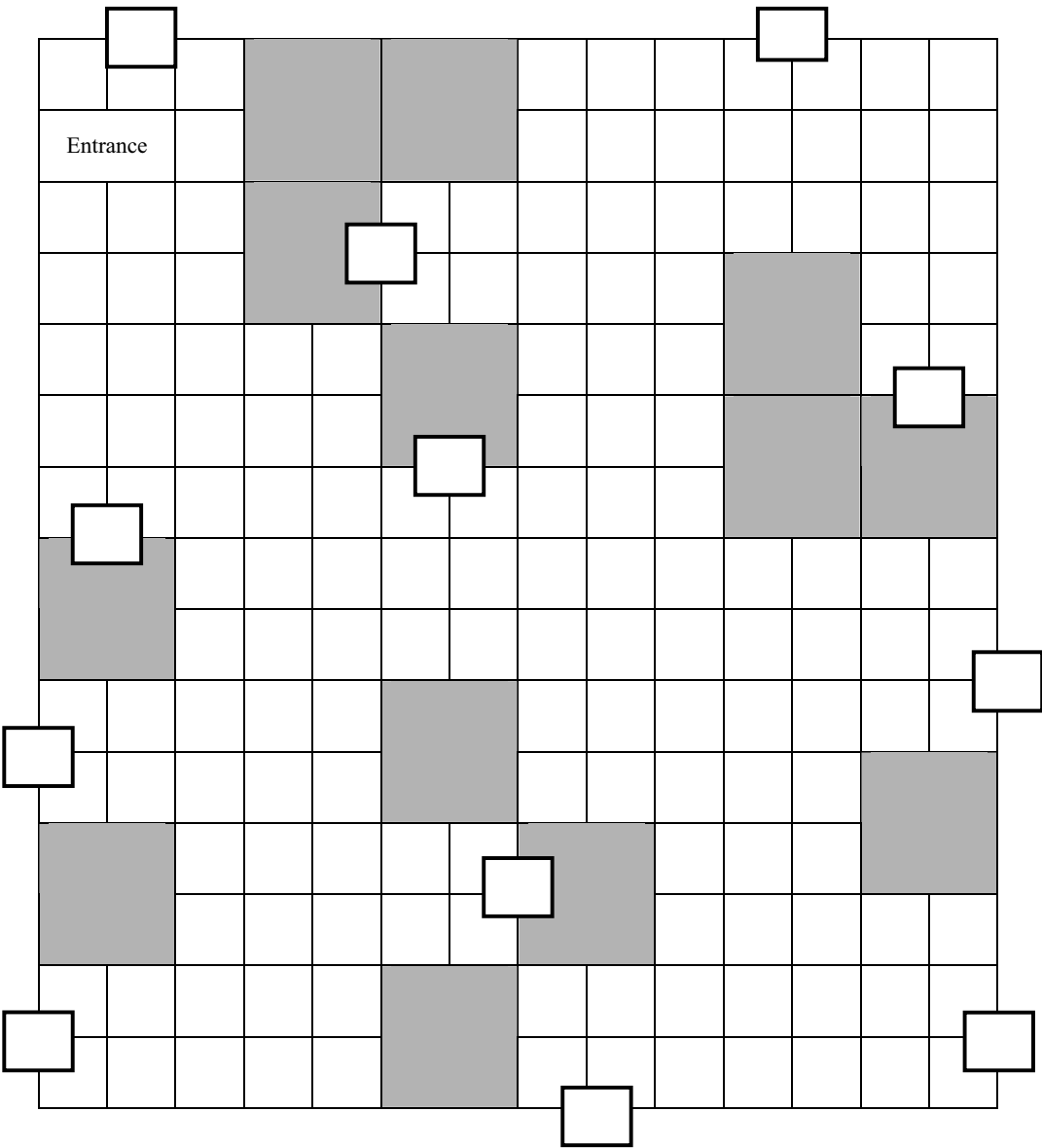
Directions: For each question below, please circle one option that best describes the degree to which you agree with the following statements.

1. Moving through the maze seemed natural to me.

    1   2   3   4   5   6   7
(strongly disagree)   (neutral)   (strongly agree)

2. I thought the maze design was confusing.

    1   2   3   4   5   6   7
(strongly disagree)   (neutral)   (strongly agree)

3. The maze didn't seem real to me.

    1   2   3   4   5   6   7
(strongly disagree)   (neutral)   (strongly agree)

4. Moving through the maze was difficult.

    1   2   3   4   5   6   7
(strongly disagree)   (neutral)   (strongly agree)

5. It was hard to remember all the objects I experienced in the maze.

    1   2   3   4   5   6   7
(strongly disagree)   (neutral)   (strongly agree)

6. It was easy to move where I wanted in the maze.

    1   2   3   4   5   6   7
(strongly disagree)   (neutral)   (strongly agree)

Participant #:_____

Directions: For each question below, write your answer in the space provided. If you need more space, you may use the back of this sheet of paper.

7. Was there anything about the system that made it difficult to move throughout the maze? If so, please describe them.

8. Was there anything about the system that made it easy to move throughout the maze? If so, please describe them.

9. Do you think you would have performed better, worse, or the same with another method of moving around the maze? If so, which?

10. Are there any other ways you would prefer to move around the environment?

11. What changes would you like to see in a later version?

12. Do you have any other comments or feedback about your experience?

Debriefing

Numerous techniques have been implemented in Virtual Environments (VEs) to allow a participant to move about a virtual space. In general, they can be categorized as either techniques that try to replicate the energy and motions of walking or as purely virtual travel techniques. Examples of the former include treadmills and walking-in-place schemes. Examples of the latter usually utilize a joystick to "fly" through a space in a direction specified by either head orientation or a handheld pointer. All these approaches assume that the physical tracked space available to the user is smaller than the virtual space that is to be experienced.

Our goal is to investigate the differences between navigation (how the user moves) in the real world and navigation in a virtual environment using different travel techniques. To assess these differences, we are performing an experiment between conditions. In one condition, the participants explore a real world maze. In the second condition, participants explore a virtual maze and are allowed to walk about the space in a natural manner. In the third condition, the participants explore a virtual maze and navigate via a joystick trigger that moves them in the direction they are looking. Participants are being given questionnaires which evaluate information gathering and cognition. We hypothesize that our results in the virtual real walking condition will be more similar to the real world than the virtual simulated walking condition.

I would like to ask you not to inform anyone else about the purpose of this study. Thank you for participating. If you have questions about the final results, please contact Evan A. Suma (687-8582, easuma@uncc.edu) or Dr. Larry F. Hodges (687-8559, lfhodges@uncc.edu).

APPENDIX C: MATERIALS FROM EXPERIMENT 3

This appendix contains materials used in Experiment 3, which was reported in Chapter 5. The following materials are included, listed in order of appearance:

1. The participant information sheet

2. The informed consent form

3. The demographic and video game experience questionnaire

4. The list of words used for the attention task

Effects of Virtual Environment
Travel Technique on Cognitive Processing

Participant Information

Part I: Informed Consent
1. We will check if you meet all the qualifications to be a participant in this study.
2. We will explain the entire experiment to you and answer any questions that you have.
3. You will be asked to review a consent form that describes aspects of the study. If you agree, please sign the form.

Part II: Pre-Experiment
1. First, you will be asked to complete a demographic survey. (approximately 3 minutes)
2. You will then be asked to complete a mental rotation test. (8 minutes)
3. Next, you will be asked to complete a spatial orientation test. (5 minutes)
4. You will then be asked to complete a questionnaire on simulator sickness. (approximately 2 minutes)
5. We will show you the equipment we will use: the head-mounted display (HMD) and a hand-held joystick. We will answer any questions you have about them.
6. We'll help you adjust the HMD so that you can see the images properly in 3D. You can ask to discontinue the experiment at any time.
7. You will then be asked to complete a virtual reality spatial orientation test. This test will take no longer than 5 minutes.

Part III: The Experiment Session
1. We will show you how to navigate in the virtual environment, and we will explain the experiment tasks to you. You will need to follow a moving target as closely as possible in the virtual environment. Audio recordings of words will also be played through the headphones, and you will be asked to press a button when the word corresponds to a certain category. We will answer any questions you may have about the experiment tasks or navigating in the virtual environment.
2. Next, you will practice the experiment tasks in a training virtual environment. Practice will take no longer than 5 minutes.
3. You will then be given up to 2 minutes to remove the HMD and rest, if you desire.
4. You will then be asked to complete 4 trials in which you will be performing the experiment tasks in the virtual environment. Each trial will take no longer than 5 minutes. After 2 out of the 4 trials, you will be asked to remove the HMD and indicate the words you recognize from the experiment on a computer monitor. In the other 2 trials, you will be given up to 2 minutes to remove the HMD and rest, if you desire.

Part IV: Post-Experiment
1. After the experiment session, you will be asked to complete a questionnaire on simulator sickness. (approximately 2 minutes)

Please answer the questions thoughtfully; your answers are a key element in making our study produce meaningful and useful results.

UNCCHARLOTTE

Department of Computer Sc
College of Computing and Inforn
9201 University City
Charlotte, NC 2

Informed Consent

Project Title and Purpose:
You are invited to participate in a research study entitled "Effects of Virtual Environment Travel Technique on Cognitive Processing." The purpose of this research is to investigate the differences between different methods of travel in immersive virtual environments. We are performing an experiment to compare real walking to joystick-based travel techniques and determine their effects on cognitive processing.

Investigator(s):
      Evan A. Suma, B.A. and Larry F. Hodges, Ph.D.
      Office: Woodward 404
      Email: easuma@uncc.edu
      Phone: 704-687-8582
      Please contact Evan Suma with questions regarding this research.

Eligibility:
You may participate in this project if you are between the ages of 18 and 65, can communicate comfortably in spoken and written English, and have use of at least one hand, good hearing, and either 20/20 vision or corrected vision to 20/20.

Description of Participation:
You will be randomly assigned to one of the different travel conditions and asked to perform a series of tasks in a virtual environment (please see the attached Participant Information sheet for a complete description of participation in this study). Information about your interactions in the environment will be logged by the computer. You will be asked to fill out questionnaires prior to and immediately following the session. The session will last about one hour. Approximately 120 people will take part in this study.

Length of Participation:
Your participation in this project will require one laboratory session lasting approximately one hour.

Risks and Benefits of Participation:
While using virtual environment systems, some people experience slight symptoms of disorientation, nausea, or dizziness. These can be similar to "motion sickness" or the feeling experienced in wide-screen movies and theme park rides. We do not expect these

to be strong or to last after participants leave the laboratory. You will often be reminded that if you feel uncomfortable and wish to stop the experiment, you are free to do so at any time without penalty by announcing you wish to stop.

During this study, you may benefit from exposure to emerging virtual reality technology that is typically inaccessible to the general public. Students in Lorrie Lehmann's and Dale-Marie Wilson's summer school courses will receive extra credit assignment grade for participating. Students in the psychology department participant pool will receive 1 research credit for participating. You will still receive credit for participating even if you wish to stop during the experiment.

Volunteer Statement:
You are a volunteer. The decision to participate in this study is completely up to you. If you decide to be in the study, you may stop at any time. You will not be treated any differently if you decide not to participate or if you stop once you have started.

Confidentiality vs. Anonymity:
The data collected by the Investigator will not contain any identifying information or any link back to you or your participation in this study. The following steps will be taken to ensure this anonymity: The data collected will be kept anonymous and confidential by randomly assigning a participant number for each participant and only referring to the data by the given participant number. Any data that is documented on paper will be stored and locked in a cabinet. Informed consent forms will also be locked away, but will be stored separately from the anonymized paper data so that the participants cannot be identified. Electronic data will be stored on a password-protected computer.

Fair Treatment and Respect:
UNC Charlotte wants to make sure that you are treated in a fair and respectful manner. Contact the university's Research Compliance Office (704-687-3309) if you have questions about how you are treated as a study participant. If you have any questions about the actual project or study, please contact Evan Suma (704-687-8582, easuma@uncc.edu).

Approval Date:
This form was approved for use on May, 11, 2009 for use for one year.

Participant Consent:
I have read the information in this consent form. I have had the chance to ask questions about this study, and those questions have been answered to my satisfaction. I am at least 18 years of age, and I agree to participate in this research project. I understand that I will receive a copy of this form after it has been signed by me and the principal investigator of this research study.

_____ _____ _____
Participant Name (PLEASE PRINT) Participant Signature   DATE

_____ _____
Investigator Signature   DATE

Demographic Questionnaire

There are 13 questions in this survey

Personal Information

1 Participant number: *

Please write your answer here:

[   ]

2 Your age: *

Please write your answer here:

[   ]

3 Your gender: *

Please choose **only one** of the following:

○ Female

○ Male

4 Are you left-handed or right-handed? If you are not sure, please choose the hand you write with. *

Please choose **only one** of the following:

○ Left-Handed

○ Right-Handed

5 Ethnicity: *

Please choose **all** that apply:

☐ American Indian or Alaska Native

☐ Asian

☐ Black or African American

☐ Hispanic or Latino

☐ Native Hawaiian or Other Pacific Islander

☐ White

☐ Prefer not to specify

Other: [   ]

6 Occupational status: *

Please choose **all** that apply:

☐ Undergraduate Student

☐ Master's Student

☐ Ph.D. Student

☐ University Staff

☐ Faculty

Other: [   ]

7 If you are a student, please indicate your major:

Please write your answer here:

[   ]

Video Game Experience

8 How long have you been playing video games? *

Please choose **only one** of the following:

- ○ I don't play video games
- ○ 6 months
- ○ 1 year
- ○ 2-5 years
- ○ 5-10 years
- ○ 10 or more years

9 During an average week, how many hours do spend playing video games? *

Please choose **only one** of the following:

- ○ 0-3
- ○ 4-7
- ○ 8-11
- ○ 12-15
- ○ 16-19
- ○ 20 or more

10 Do you consider yourself a... *

Please choose **only one** of the following:

- ○ Hardcore gamer
- ○ Casual gamer
- ○ Not a gamer
- ○ Don't know

11 What kinds of computer or video games do you like to play? *

Please choose **all** that apply:

- ☐ None
- ☐ Puzzle games (ex. Tetris, Bejeweled, Collapse)
- ☐ Arcade games (ex. Pacman, Galaga, Frogger)
- ☐ Platform games (ex. Mario, Sonic the Hedgehog, Little Big Planet)
- ☐ Sports games (ex. Madden, NBA titles)
- ☐ Racing/Driving games (ex. Need for Speed, Burnout Paradise)
- ☐ Adventure games (ex. King's Quest, The Longest Journey, Monkey Island)
- ☐ Music games (ex. Dance Dance Revolution, Guitar Hero, Rock Band)
- ☐ First-person shooter games (ex. Half-Life, Gears of War, Quake, Halo)
- ☐ Fighting games (ex. Mortal Kombat, Street Fighter)
- ☐ Strategy games (ex. Age of Empires, Starcraft, Civilization, Warcraft)
- ☐ Simulation games (ex. The Sims, Roller Coaster Tycoon)
- ☐ Role-playing games (ex. Neverwinter Nights, Final Fantasy, Zelda, Oblivion)
- ☐ Massively multiplayer online games (ex. World of Warcraft, Age of Conan, EVE Online)

Other: [_____]

12 Think about the the times you've played games that take place in a 3D environment. How experienced are you at playing these types of games? *

Please choose **only one** of the following:

- ○ Not experienced at all
- ○ A little experienced
- ○ Experienced
- ○ Very experienced

13 Think about the times you've used online virtual worlds, such as Second Life. How experienced are you with using these virtual worlds? *

Please choose **only one** of the following:

- ○ Not experienced at all
- ○ A little experienced
- ○ Experienced
- ○ Very experienced

Word Lists

HOUSE PARTS LIST A	HOUSE PARTS LIST B	HOUSE PARTS LURE LIST A	HOUSE PARTS LURE LIST B
cupboard	den	biscuit	sapling
bathtub	foyer	spacecraft	soda
chimney	stairway	web	towel
attic	closet	ticket	jar
lobby	bathroom	label	canvas
basement	cellar	shirt	bullet
porch	ceiling	football	chicken
roof	bedroom	motor	wheel
window	kitchen	season	ball
floor	hall	market	paper
door	room	thing	country

BODY PARTS LIST A	BODY PARTS LIST B	BODY PARTS LURE LIST A	BODY PARTS LURE LIST B
toe	ankle	duck	cork
elbow	hip	coin	puzzle
liver	lungs	essay	toast
tooth	ear	drug	barrel
knee	tongue	fruit	fish
finger	stomach	cotton	stick
brain	throat	ring	suit
chest	leg	soil	wood
nose	shoulder	scale	beach
arms	eye	test	game
hand	head	water	system